^{39}Ar-^{40}Ar Ages of Eucrites and the Thermal History of Asteroid 4-Vesta

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Submitted to Meteoritics & Planetary Science, October, 2002

ABSTRACT

Eucrite meteorites are igneous rocks that derive from a large asteroid, probably 4 Vesta. Prior studies have shown that after eucrites formed, most were subsequently metamorphosed to temperatures up to ≥800°C, and much later many were brecciated and heated by large impacts into the parent body surface. The uncommon basaltic, unbrecciated eucrites also formed near the surface but presumably escaped later brecciation, whereas the cumulate eucrites formed at depth where metamorphism may have persisted for a considerable period.

To further understand the complex HED parent body thermal history, we determined new ^{39}Ar-^{40}Ar ages for nine eucrites classified as basaltic but unbrecciated, six eucrites classified as cumulate, and several basaltic-brecciated eucrites. Relatively precise Ar-Ar ages of two cumulate eucrites (Moama and EET87520) and four unbrecciated eucrites give a tight cluster at 4.48 ±0.01 Gyr. Ar-Ar ages of six additional unbrecciated eucrites are consistent with this age, within their larger age uncertainties. In contrast, available literature data on Pb-Pb isochron ages of four cumulate eucrites and one unbrecciated eucrite vary over 4.4-4.515 Gyr, and ^{147}Sm-^{143}Nd isochron ages of four cumulate and three unbrecciated eucrites vary over 4.41-4.55 Gyr. Similar Ar-Ar ages for cumulate and unbrecciated eucrites imply that cumulate eucrites do not have a younger formation age than basaltic eucrites, as previously proposed. Rather, we suggest that these cumulate and unbrecciated eucrites resided at depth where parent body temperatures were sufficiently high to cause the K-Ar and some other chronometers to remain open diffusion systems. From the strong clustering of Ar-Ar ages at ~4.48 Gyr, we propose that these meteorites were excavated from depth in a single large impact event ~4.48 Gyr ago, which quickly cooled the samples and started the K-Ar chronometer. A large (~460 km) crater postulated to exist on Vesta may be the source of these eucrites and of many smaller asteroids thought to be spectrally or physically associated with Vesta. Some Pb-Pb and Sm-Nd ages of cumulate and unbrecciated eucrites are consistent with the 4.48 Gyr Ar-Ar age, and the few older Pb-Pb and Sm-Nd ages may reflect isotopic closure prior to the large cratering event.

One cumulate eucrite gives an Ar-Ar age of 4.25 Gyr; three additional cumulate eucrites give Ar-Ar ages of 3.4-3.7 Gyr; and two unbrecciated eucrites give Ar-Ar ages of ~3.55 Gyr. We attribute these younger ages to later impact heating. In addition, we find Ar-Ar impact-reset ages of several brecciated eucrites and eucritic clasts in howardites to fall in the range of 3.5-4.1 Gyr. Among these, Piplia Kalan, the first eucrite to show evidence for extinct ^{26}Al, was strongly impact heated ~3.5 Gyr ago. When these data are combined with eucrite Ar-Ar ages in the literature, they confirm the previous suggestion that several large impact heating events occurred on Vesta over the time period ~4.1-3.4 Gyr ago. The onset

of major impact heating may have occurred at similar times for both Vesta and the Moon, but impact heating appears to have persisted to a somewhat later time on Vesta compared to the Moon.

1. INTRODUCTION

Eucrites are igneous meteorites produced by crystallization from a melt on a large asteroidal parent body, probably 4 Vesta (McCord et al 1970; Binzel & Xu, 1993). Although eucrites rank among the oldest analyzed basalts in the solar system, they have experienced a complex thermal history that left its mark on a variety of characteristics ranging from mineral textures to isotopic chronologies. The thermal processing observed in eucrites has two sources – internal parent body metamorphism, probably produced by decay of short-lived nuclides, and heating produced by impact cratering on the parent body. The extensive thermal history of eucrites is consistent with their derivation from an asteroid larger than that of most meteorites types, yet smaller than planetary bodies such as the Moon and Mars, whose analyzed basalts were formed much later. Thus, eucrites present an opportunity to study basalt generation on a body of significant size very early in solar system history, and to assess the long-term thermal history of that parent body. Much of this kind of information is not available for the Earth, Moon, and Mars.

Most eucrites probably formed as surface basalt flows >4.555 Gyr ago, or shortly after accretion of the HED (howardite-eucrite-diogenite) parent body. A Pb-Pb model age of 4.560 ±0.003 Gyr was reported for the Ibitira eucrite by two laboratories, and similarly old (although less precise) ^{147}Sm-^{143}Nd ages have been reported for a few eucrites (Carlson and Lugmair, 2000, and references therein). The existence of decay products of short-lived nuclides in some eucrites also requires their early formation. For example, evidence for live ^{53}Mn (half-life 3.8 Myr), ^{26}Al (half-life 0.7 My), and ^{60}Fe (half-life 0.1 Myr) have been reported in several eucrites (Carlson & Lugmair, 2000; Srinivasan et al., 1999; Shukolyukov and Lugmair, 1993; Nyquist et al., 2001; Srinivasan, 2002). Based on ^{53}Mn and Pb-Pb data, Lugmair and Shukolyukov (1998) suggested that the HED parent body formed 4,564.8 ±0.9 Myr ago. On the other hand, many radiometric ages (K-Ar, Pb-Pb, Rb-Sr, Sm-Nd) of eucrites are considerably younger than 4.56 Gyr and variable (Bogard, 1995; Carlson and Lugmair, 2000). The reason for this variation in eucrite ages is the focus of this paper.

After their formation, most eucrites experienced metamorphism to ≥800°C, which was sufficient to cause Mg, Fe, and Ca in pyroxenes to undergo varying degrees of subsolidus diffusion and to produce more limited ranges of pyroxene compositions (Takeda and Graham, 1991; Yamaguchi et al., 1997).

Several models have been proposed to accomplish this metamorphism, including early differentiation of the parent body into layers (Takeda, 1979; Takeda, 1997), heating during formation of large impact craters (Nyquist et al. 1986), and heating at several kilometers depth after rapid generation and burial of multiple layers of surface basalt (Yamaguchi et al, 1996; Yamaguchi et al. 1997). Although it is difficult to date directly the time of this eucrite metamorphism, most likely it occurred very early in eucrite history. The first and third models above imply that metamorphism occurred within a few million years after basalt formation.

Most eucrites (and all howardites) are breccias formed by impact events near the parent body surface. These impacts not only can disturb the texture and mineralogy, but also can reset isotopic ages (Bogard, 1995; Kunz et al 1995). Because the K-Ar chronometer is especially sensitive to only moderate heating in crater ejecta, ^{39}Ar-^{40}Ar ages of almost all eucrites and howardites show disturbance and resetting. Further, Rb-Sr, Pb-Pb, and Sm-Nd ages of some eucrites are also disturbed and/or reset. Bogard (1995) summarized available impact-reset ages of eucrites and suggested that the HED parent body had experienced an analogous cataclysmic bombardment to that which reset the radiometric ages of many lunar highland rocks returned by Apollo and Luna missions. The observation that such impact-reset ages are not commonly observed in most other meteorite types was attributed to the relatively large size of the HED parent body compared to parent bodies of most other meteorite types. Large size is a requirement in order to produce large crater deposits that remain hot for a significant time, without disrupting the parent body.

Two uncommon types of eucrites, the unbrecciated, metamorphosed, basaltic eucrites and the cumulate eucrites, give neither very old (i.e., >4.55 Gyr) ages nor much younger impact reset ages. Rather, their radiometric ages are intermediate. Four cumulate eucrites gave Pb-Pb and Sm-Nd isochron ages between 4.40 and 4.55 Gyr, and three unbrecciated eucrites gave Sm-Nd isochron ages of 4.46-4.54 Gyr (Tera et al., 1997; Yamaguchi et al., 2001; Carlson and Lugmair, 2000). The ^{39}Ar-^{40}Ar ages for two of these unbrecciated eucrites are ~4.49 Gyr (Bogard & Garrison, 1995; Yamaguchi et al., 2001). For the unbrecciated eucrite EET90020, Yamaguchi et al (2001) suggested that its Sm-Nd and Ar-Ar ages were reset during formation of a very large crater on Vesta. Although it is conceivable that the ages of cumulate eucrites are somehow linked to this large Vesta crater, it is also possible that they were caused by sustained metamorphism deep within the parent body. From the published data, it is not clear whether the various ages of cumulate and unbrecciated eucrites represent a single heating event or a broad spectrum of metamorphic and impact heating. Tera et al. (1997) suggested that the range of Pb-Pb and Sm-Nd ages of cumulate eucrites represented different times of formation, or at least of isotopic closure.

In this paper we present a large amount of new data on the ^{39}Ar-^{40}Ar ages of eucrites. Several of these newly analyzed meteorites are classified as unbrecciated, and others are classified as cumulate. Some of these give older ages, whereas others give younger ages consistent with later impact resetting. We discuss and interpret these ages, along with literature data, in the context of the possible metamorphic and impact thermal history of the HED parent body, which we presume to be Vesta.

2. METHODS

Most analyzed eucrite samples were whole rock chips each weighing several tens of milligrams. Samples were neutron irradiated in several batches at different times. Each irradiation included several samples of the NL-25 hornblende, which is 2.65 Gyr in age (Bogard et al., 1995) and which serves as a flux and age monitor. Argon was released by stepwise temperature extraction in a furnace equipped with a thermocouple, and the Ar isotopic composition was measured on a mass spectrometer. Most measurements were made using a Nuclide 6-60 instrument, but a few samples having very low potassium concentrations were measured on a VG-3600 instrument having lower Ar background. Isotopic data were corrected for system blanks, radioactive decay, and reactor-produced isotopic interferences. The $^{39}Ar/^{37}Ar$ correction factor was determined by irradiating several samples of pure CaF_2 crystals. Ar-Ar ages were calculated using the ^{40}K decay parameters recommended by Steiger and Jäger (1977). Uncertainties assigned to calculated ages for individual temperature extractions shown in the Ar age spectra include uncertainties in $^{40}Ar/^{39}Ar$ ratio measurements and in all applied corrections, but do not include the uncertainty in the irradiation constant (J) value. An event age usually is derived from the mean of the ages of several extractions, i.e., an age plateau. The event age uncertainty given is the one-sigma uncertainty in this mean age, statistically combined with the determined uncertainty in J for that sample (see Bogard et al, 2000). Similarly, where we refer to the specific age of an individual extraction in the context of an event age, its age uncertainty also contains the uncertainty in J. None of the Ar-Ar age uncertainties presented here consider uncertainties in the absolute age of the NL-25 hornblende (believed <0.5%) or in ^{40}K decay constants, but these do not effect comparison of relative Ar-Ar ages obtained in the JSC laboratory.

In interpreting the Ar-Ar age spectra for these samples, we consider the behavior of all Ar isotopic ratios as a function of extraction temperature. For example, rapidly decreasing $^{36}Ar/^{37}Ar$, $^{36}Ar/^{38}Ar$, and K/Ca ratios in the first few extractions are interpreted to indicate adsorbed atmospheric Ar and terrestrial weathering, whereas constant $^{36}Ar/^{37}Ar$ and $^{36}Ar/^{38}Ar$ ratios at intermediate and higher temperatures are interpreted to indicate a lack of terrestrial Ar. A sudden decrease in the K/Ca ratio at higher extraction temperature is an indicator that pyroxene has begun to degas its Ar. A decrease in Ar age associated with this decrease in K/Ca can be an indicator of implanted ^{39}Ar (produced in the reactor from the reaction ^{39}K (n,p) ^{39}Ar), which has recoiled from surfaces of K-rich feldspar grains into surfaces of K-poor pyroxene grains.. Distinct peaks in the rate of release of ^{39}Ar with temperature may also suggest that K occurs in phases with different Ar diffusion properties, such as zoned feldspar grains or grain populations having different sizes. This type of detailed analysis of Ar isotopic data is discussed in Garrison et al. (2000).

We do not make extensive use of isochron plots of ^{40}Ar/^{36}Ar versus ^{39}Ar/^{36}Ar, as is commonly done for terrestrial samples. Although isochron plots have been used to evaluate meteorite Ar-Ar data, they can be misleading and are, in most respects, less informative than the Ar-Ar age spectrum. Unlike the case for terrestrial samples, it is the existence of mineral phases having different ratios of radiogenic Ar to cosmogenic ^{36}Ar that produces a linear isochron in eucrites. The cosmogenic ^{36}Ar is not generally well-correlated with any radiogenic component, or with any trapped Ar, excess ^{40}Ar, or reactor-recoiled ^{39}Ar. The slope of an isochron plot for eucrites, from which the age is derived, is primarily determined by the larger ^{40}Ar/^{36}Ar and ^{39}Ar/^{36}Ar ratios arising from degassing of feldspar at intermediate temperatures. In contrast, the ^{40}Ar/^{36}Ar intercept value of the isochron is primarily determined by high temperature extractions degassing pyroxene, for which larger releases of cosmogenic ^{36}Ar produce lower ^{40}Ar/^{36}Ar and ^{39}Ar/^{36}Ar ratios. However, these same extractions releasing ^{36}Ar from pyroxene are often the same ones that show lower Ar-Ar ages due to the gain of recoiled ^{39}Ar produced in the reactor. This situation means that, on the isochron plot, those extractions releasing more ^{36}Ar and plotting closer to the origin may also give slightly younger ages. As a consequence, the isochron can be rotated counter-clockwise, thereby giving an older apparent age and a lower ^{40}Ar/^{36}Ar intercept. In fact, meteorites showing lowered Ar-Ar ages at higher temperatures caused by gain of recoiled ^{39}Ar commonly show negative ^{40}Ar/^{36}Ar intercepts on isochron plots. Such negative intercepts have no physical meaning in terms of a trapped component, but can be an indicator of redistribution of recoiled ^{39}Ar. Even in cases where there is no obvious effect of ^{39}Ar recoil on the age spectrum, situations can exist where the isochron gives a false age. For example, occasionally we observe that the ^{39}Ar is released in two distinct phases, and the higher temperature phase shows both a lower ^{39}Ar/^{36}Ar ratio and an older age. In this case the isochron can be rotated clock-wise and yield an isochron age that is too young. We shall illustrate these subtle phenomena with isochrons in discussing some of the individual eucrite data below.

3. ^{39}AR-^{40}AR AGE RESULTS AND SAMPLE DESCRIPTIONS

We recently analyzed several Antarctic eucrites that have been described as being either unbrecciated or cumulate. Including some previously published data, we now have analyzed the three unbrecciated eucrites with reported Pb-Pb and/or Sm-Nd ages and three of the four cumulate eucrites with reported Pb-Pb and Sm-Nd isochron ages, as well as several additional meteorites. Ar isotopic data are given in Appendix 1. Some of these new Ar-Ar results were previously reported in abstracts. Below we discuss the Ar-Ar data and derive an age for individual samples.

3.1 Unbrecciated Basaltic Eucrites

Basaltic eucrites are pigeonite-plagioclase rocks having fine to medium grain sizes (Mittlefehldt et al., 1998a). They are thought to have formed as extrusive flows or shallow intrusions on the parent asteroid. Post-formational annealing has caused the original mineral pigeonite to undergo subsolidus exsolution of augite. The degree of post-formational thermal annealing varies among basaltic eucrites, and a metamorphism classification scheme was defined by Takeda and Graham (1991). The lowest metamorphic class (#1) shows narrow augite lamellae and preservation of the original igneous zoning texture. The highest metamorphic class (#6) shows much wider augite lamellae, and solid state diffusion of Mg and Fe has caused the pyroxene composition to become nearly homogeneous, and in some cases, has caused the pyroxene to partly invert to orthopyroxene. Plagioclase in basaltic eucrites can show a wide range in anorthite content, and is probably the only significant K-bearing mineral. Most basaltic eucrites are breccias and consist of clasts of either similar basalt types (monomict) or different rock types (polymict), often set in a fine-grained, fragmental matrix. Eucritic clasts also occur in howardites, which are mixtures of eucritic and diogenitic material. The brecciated nature of most eucrites can make their determined isotopic chronologies difficult to decipher. However, a small fraction of eucrites appear unbrecciated, meaning that they do not give evidence of having been broken and mixed by impacts at their parent body surface. The Ar-Ar ages of several unbrecciated basaltic eucrites are presented in this section.

QUE97053. This 75 g unbrecciated eucrite (weathering category A) is coarse grained and shows pervasive shock effects (JSC Antarctic Meteorite Newsletter online). The Ar-Ar age spectrum for QUE97053 is shown in Fig. 1a. The $^{36}Ar/^{37}Ar/^{38}Ar$ ratios indicate that only the first temperature extraction released significant atmospheric Ar. Overall the Ar-Ar age spectrum is relatively flat, and those few extractions releasing the first ~4% of the ^{39}Ar suggest modest diffusion loss of ^{40}Ar. A very small decline in age for four extractions releasing ~45-60% of the ^{39}Ar occurs at the point that the K/Ca ratio starts to decrease, and this age decrease may have been produced by the implantation of recoiled

^{39}Ar into pyroxene grain surfaces. The summed Ar-Ar age for all extractions above ~4% ^{39}Ar release is 4.468 ±0.021 Gyr, and this would be a lower limit to the time of K-Ar closure. If we omit these four low-age extractions (releasing over 45-60% of the ^{39}Ar), and omit two extractions releasing ~4-13% ^{39}Ar (which may have recently lost ^{40}Ar by diffusion), then 12 remaining extractions releasing 72% of the total ^{39}Ar give an average age of 4.476 ±0.014 Gyr. However, slightly higher ages exist for the extractions releasing at >80% ^{39}Ar release. For example, nine extractions releasing ~12-79% of the ^{39}Ar (but omitting the four low ages at ~45-60% ^{39}Ar) give an age of 4.471 ±0.012 Gyr, whereas three extractions releasing ~80-100% of the ^{39}Ar give an age of 4.486 ±0.007 Gyr. Giving slightly greater weighing to the older age, we adopt an age of 4.480 ±0.015 Gyr as the time of last significant Ar degassing of QUE97053.

GRA98098. This 779 g unbrecciated eucrite (weathering category B) is a recrystallized, granular aggregate and possesses a texture and chemical composition atypical of other eucrites (Mittlefehldt and Lee, 2001). The Ar-Ar age spectrum for a whole rock sample is shown in Fig. 1b. The $^{36}Ar/^{37}Ar/^{38}Ar$ ratios indicate that only the first two extractions released significant amounts of terrestrial atmospheric Ar. The K/Ca ratio decreases throughout most of the extraction and suggests that degassing of multiple mineral phases significantly overlap. None of the extractions suggest significant ^{39}Ar recoil effects. However, the age does increase slightly with extraction temperature. Nine extractions releasing ~16-69% of the ^{39}Ar give an age of 4.453 ±0.015 Gyr. Seven extractions releasing ~69-90% of the ^{39}Ar give an age of 4.473 ±0.012 Gyr. The age of these combined 16 extractions (releasing 74% of the total ^{39}Ar) is 4.459 ±0.012 Gyr. The 1425°C extraction releasing ~90-99% of the ^{39}Ar gives an even higher age of 4.511 ±0.010 Gyr. This slope in the age spectrum has two possible explanations. First, it could signify not quite complete degassing of ^{40}Ar by an impact event ~4.45 Gyr ago. Secondly, the age slope may represents closure of the K-Ar chronometer in different K lattice sites over an extended period of time during very slow cooling of the meteorite deep in the parent body. A similar explanation was argued for sloped Ar-Ar age spectra observed in several mesosiderites (Bogard and Garrison, 1995). We will adopt an age of 4.45 ±0.01 Gyr for the case of impact degassing and an age of 4.49 ±0.02 Gyr for the case of the early stages of slow cooling.

The isochron plot ($^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$) for 17 extractions of GRA98098 (12-90% ^{39}Ar release) is highly linear (R^2= 0.9998) and gives a younger age of 4.444±0.006 Gyr and a $^{40}Ar/^{36}Ar$ intercept of 5 ±3. All 17 extractions, except two, give ages that are older than this isochron age by significant amounts. Even the upper limit to the isochron age (4.45 Gyr) is younger than either plateau age. This is an example of a false isochron mentioned above for the case where the Ar age increases with extraction temperature and the higher temperature extractions have lower $^{39}Ar/^{36}Ar$ ratios. As a consequence, the higher temperature extractions, plotting closer to the origin, have slightly higher $^{40}Ar/^{36}Ar$ ratios than lower temperature extractions, and the isochron plot has rotated slightly clockwise.

The Ar-Ar age spectrum for a vein of impact melt in GRA98098 is shown in Fig. 1c. Except for the last extraction (which released very little Ar), both the $^{36}Ar/^{37}Ar$ and $^{36}Ar/^{38}Ar$ ratios are nearly constant. Unfortunately, the first extraction was greatly overheated (accidentally) and released 81% of the total ^{39}Ar. Its age of 4.40 Gyr probably reflects some diffusive loss of ^{40}Ar. For subsequent extractions, the Ar-Ar age varies between 4.46 and 4.48 Gyr. Thus, we conclude that this impact melt vein probably has a similar age as the whole rock sample.

PCA82502. This 890 g unbrecciated eucrite is listed as weathering category A (Mason et al., 1989), but has not been studied in detail. Its Ar-Ar age spectrum and K/Ca ratios as a function of ^{39}Ar release are shown in Fig. 1d. Several extractions releasing the first ~20% of total ^{39}Ar suggest some diffusive loss of ^{40}Ar. The $^{36}Ar/^{37}Ar$ and $^{36}Ar/^{38}Ar$ ratios indicate that only the first extraction released significant amounts of adsorbed terrestrial Ar. The K/Ca ratios and relative rate of release of ^{39}Ar with extraction temperature suggest that a change in phases degassing Ar occurs at ~60% ^{39}Ar release, and a decrease in the Ar-Ar age begins to occur there also. The summed Ar-Ar age above ~ 12% ^{39}Ar release is 4.45 Gyr and is a lower limit to the last significant degassing event. Between ~22% and ~55% ^{39}Ar release, five extractions with identical ages (within mutual uncertainties) show constant K/Ca and give an average age of 4.506 ±0.009 Gyr. At even higher extraction temperatures a second phase of lower K/Ca begins degassing and the age decreases, then increases again. This age decrease is likely caused by ^{39}Ar recoil into grain surfaces of pyroxene. The source of this recoiled ^{39}Ar, surfaces of feldspar grains, probably degasses at low temperatures and is masked by ^{40}Ar diffusive loss. After these pyroxene grain surfaces have released their recoiled ^{39}Ar, the Ar-Ar age from high-temperature plagioclase sites returns almost to the age level shown prior to the start of Ar degassing from pyroxene. We have observed this type of recoil behavior in several other meteorites. Thus, we adopt the 4.506 Gyr plateau age as giving the time of the last significant thermal event experienced by the meteorite.

The isochron plot of $^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$ (R^2=0.9965) for those 14 extractions releasing 12-100% of the ^{39}Ar yields an age of 4.512 ±0.028 Gyr and a negative $^{40}Ar/^{36}Ar$ intercept of –40 ±29. This isochron age is greater than ages of all 14 extractions, except one, for which it is the same. Again, this is a false isochron age. As discussed above, excess recoiled ^{39}Ar and younger ages are associated with lower $^{39}Ar/^{36}Ar$ ratios compared to those extractions which define the plateau age. As a consequence the isochron has been rotated counter-clockwise, producing a larger slope (and isochron age) and a negative intercept.

PCA91007. This 223 g unbrecciated eucrite (weathering category A/B) contains vesicles and is only moderately metamorphosed, with the original igneous texture being largely preserved (Warren et al. 1996). These authors suggested that this meteorite might represent the best example among eucrites of a quenched melt. Its Ar-Ar age spectrum (Fig. 1e) resembles that of PCA82502, but ^{40}Ar diffusive loss and ^{39}Ar recoil redistribution are even more pronounced. The first few extractions (~0-13% ^{39}Ar release) show higher K/Ca ratios and much lower ages and suggest weathering mobilization of K and its redistribution onto grain surfaces. However, only the first extraction suggests significant amounts of adsorbed terrestrial Ar. Three extractions releasing ~27-49% of the ^{39}Ar show the same age (within their uncertainties), as well as constant K/Ca ratios, and give an average age of 4.444 ±0.008 Gyr. The age then decreases just prior to a decrease in K/Ca, then increases again at higher temperatures, although it does not return to its previous high value. We attribute this behavior to ^{39}Ar recoil, as discussed above. It is not clear whether the 4.444 Gyr plateau age defined over 27-49% ^{39}Ar release is the actual K-Ar closure time, or has been lowered by ^{40}Ar diffusion loss and/or ^{39}Ar recoil gain. Thus we take 4.44 Gyr as a lower limit to the time of K-Ar closure.

Caldera. The Caldera, Chile find has a chemical composition similar to main group eucrites, and its pyroxene suggests prolonged annealing (Boctor et al., 1994) After Ibitira, Caldera was the second unbrecciated, non-cumulate eucrite recognized. Our sample (obtained from R. Haig) was friable and appeared extensively weathered. The Ar age spectrum (Fig. 1f) suggests Ar release in three stages. As with PCA91007, the first few extractions (~0-15% ^{39}Ar release) show much higher K/Ca ratios and much lower ages and suggest weathering mobilization of K and its redistribution onto grain surfaces. These first few extractions also show significant amounts of adsorbed terrestrial Ar, and corrections for air-Ar on the first extraction lowers its age to nearly zero. Over ~20-65% ^{39}Ar release, the K/Ca ratio is constant and the Ar-Ar age slowly increases, as might be expected if this meteorite phase had experienced a small amount of recent diffusive loss of ^{40}Ar caused by terrestrial weathering. Above ~65% ^{39}Ar release the K/Ca decreases slightly and a small ^{39}Ar recoil effect appears. The single 1400°C extraction released 18% of the total ^{39}Ar and gives an age of 4.493 ±0.012 Gyr. This age is a lower limit to the last time of closure and is probably close to the actual K-Ar closure age of Caldera. Carlson and Lugamir (2000) report for Caldera a Pb-Pb age of 4.516 ±0.003 Gyr and a Sm-Nd age of 4.544 ±0.019 Gyr. Based on ^{146}Sm-^{142}Nd, ^{147}Sm-^{143}Nd, and ^{53}Mn-^{53}Cr data, Wadhwa & Lugmair (1996) give a formation age of 4.537 ±0.012 Gyr. The Ar-Ar age is smaller than this Sm-Nd age by an amount that is slightly greater than the combined age uncertainties, but is within uncertainties of the Pb-Pb age. But as will be discussed later, this is not necessarily an argument that the actual K-Ar closure time for Caldera was earlier than ~4.49 Gyr.

Asuka-881388. This is a fine-grained, crystalline eucrite with a granulitic texture, which has been thermally annealed (Takeda et al. 1997). Its Ar-Ar age spectrum is given in Fig. 1g. Slightly higher K/Ca ratios and small amounts of ^{40}Ar loss in the first ~13% of the ^{39}Ar release are probably terrestrial weathering effects. Six extractions releasing ~13-77% of the ^{39}Ar show the same age within their uncertainties and define an Ar-Ar age of 4.480 ±0.007 Gyr. If we include a seventh extraction at ~90% ^{39}Ar release, this age becomes 4.481 ±0.007 Gyr. The small decrease in age at 77-88% ^{39}Ar release occurs from grain surfaces of a phase with much lower K/Ca and is most probably a small ^{39}Ar recoil effect. The isochron plot for 12 extractions (~26-100% ^{39}Ar) of this meteorite is highly linear (R^2=0.9999) and gives a precise age of 4.491 ±0.008 Gyr and a negative ^{40}Ar/^{36}Ar intercept of –7.6 ±3.3. This isochron age is larger than all individual extraction ages, however, and both the isochron age and intercept are false. As explained above, recoil of ^{39}Ar into pyroxene has rotated the isochron slightly counter-clockwise to produce an older age and negative intercept.

Asuka-881467. This is a 38 g, unbrecciated, medium-grained, porphyritic eucrite (Yanai, 1993). The Ar-Ar age spectrum is given in Fig. 1h. Much higher K/Ca ratios and very low apparent ages for the first two extractions (~0-26% ^{39}Ar release) are weathering effects probably caused by mobilization and deposition of K on grain surfaces. (The ^{36}Ar/^{37}Ar/^{38}Ar ratios indicate that the first two extractions released significant amounts of adsorbed terrestrial Ar, and atmospheric ^{40}Ar probably accounts for all of the ^{40}Ar measured in these two extractions.) Extractions releasing ~28-40% ^{39}Ar suggest a modest amount of ^{40}Ar diffusive loss. Three extractions (~45-62% ^{39}Ar release) give the same age of 4.45 Gyr within their uncertainties. A decrease in age at ~71-81% ^{39}Ar release occurs just prior to the point at which K/Ca decreases and suggests gain of recoiled ^{39}Ar. Ten extractions releasing ~40-100% ^{39}Ar (but omitting the three extractions with the youngest ages) gives an average age of 4.42 ±0.04 Gyr. However, the highest observed age is 4.465 ±0.008 Gyr for a single extraction at 91-99% ^{39}Ar release. Because diffusive ^{40}Ar loss and recoiled ^{39}Ar have probably affected much of the age spectrum, ~4.46 Gyr is probably a better estimate of the time of K-Ar closure.

GRO95533. This 613 g eucrite (weathering category A/B) is unbrecciated, but pyroxene crystals have been granulated (JSC Antarctic Meteorite Newsletter online). The Ar-Ar age spectrum is shown in Fig. 1i. The ^{36}Ar/^{37}Ar and ^{36}Ar/^{38}Ar ratios are nearly constant after the first extraction and indicate that only the first extraction released adsorbed terrestrial Ar. This means that the slightly higher ages at ~1-16% ^{39}Ar release are not produced by terrestrial ^{40}Ar, nor can the lower Ar-Ar ages at intermediate extraction temperatures be the result of ^{40}Ar loss caused by weathering. Consequently, we interpret the higher ages at 1-16% ^{39}Ar release to be the result of loss of recoiled ^{39}Ar. The shape of the age spectrum over 16-100% ^{39}Ar release resembles that expected if the sample had been extensively degassed of ^{40}Ar by impact heating (Turner, 1969). The time of this degassing event is approximately determined by the minimum in the age spectrum. Four extractions, showing the same age within their mutual uncertainties and releasing ~16-58% of the ^{39}Ar, give an average age of 3.557 ±0.016 Gyr. That ^{39}Ar implanted into pyroxene grain surfaces after recoil is expected to degas around 80-95% ^{39}Ar release, where the K/Ca ratio substantially decreases and the age sharply increases. This implanted ^{39}Ar probably has depressed the smooth curvature of the expected age spectrum in this region. We infer that the degassing event seen by GRO95533 occurred 3.55 ±0.03 Gyr ago, which places it in the range of eucrite degassing ages previously documented for the HED parent body (Bogard, 1995).

QUE97014. The Ar-Ar age spectrum for this 142 g unbrecciated eucrite (weathering category A) is shown in Fig. 1j. The third extraction was accidentally overheated and released ~45% of the total ^{39}Ar. The $^{36}Ar/^{37}Ar/^{38}Ar$ ratios indicate that only the first extraction released a significant amount of terrestrial Ar. Several extractions releasing ~88-98% of the ^{39}Ar show a decrease in age and K/Ca ratios, probably due to gain of recoiled ^{39}Ar. Although the 3.544 ±0.007 Gyr age of the third extraction could be influenced by ^{39}Ar recoil loss, six subsequent extractions give nearly the same age. The Ar age of 7 extractions releasing ~2-85% of the ^{39}Ar is 3.540 ±0.026 Gyr. We conclude that 3.54 ±0.04 Gyr is the time of the impact event that totally reset K-Ar in this meteorite. This degassing time is the same as that for GRO95533, although the two meteorites were recovered at different Antarctic locations. The isochron plot (R^2=0.9996) for all extractions except the first two give an age of 3.577 ±0.005 (1σ) Gyr and a $^{40}Ar/^{36}Ar$ intercept of –49 ±13. As with some other samples, the isochron plot gives false results due to counter-clockwise rotation caused by recoiled ^{39}Ar.

Ibitira and EET90020. The ^{39}Ar-^{40}Ar age spectra we measured for these two unbrecciated eucrites were reported previously. Ibitira is fine-grained, vesicular, and shows a metamorphic grade of 5 (Steele and Smith, 1976; Takeda and Graham, 1991). In the Ar-Ar age spectrum (Bogard and Garrison, 1995), five extractions releasing ~14-89% of the ^{39}Ar define an age of 4.487 ±0.016 Gyr. (Note that this age differs slightly form that previously reported because of a change in the manner which we calculate plateau ages.) Although not vesicular, EET90020 contains two phases having different grain sizes, separated by vugs, and also shows type 5 metamorphism (Yamaguchi et al., 2001). The two phases yield essentially identical Ar-Ar age spectra, and no significant ^{39}Ar recoil effects are apparent in either age spectrum (Yamaguchi et al., 2001). For the fine-grained sample, eight extractions releasing ~14-98% of the ^{39}Ar define an age of 4.489 ±0.013 Gyr. For the coarse-grained sample, eight of nine extractions releasing ~8-95% of the ^{39}Ar define an age of 4.486 ±0.008 Gyr. No evidence exists in either EET90020 age spectrum for significant amounts of additional ^{40}Ar loss.

3.2 Cumulate Eucrites

Cumulate eucrites are coarse-grained gabbros principally composed of low-Ca pyroxene and calcic plagioclase. They are believed to have formed at some depth in their parent body. Extensive annealing has caused the original pigeonite to undergo complex subsolidus exsolution of augite and sometimes inversion to orthopyroxene, with the result that some meteorites contain multiple pyroxene phases (see Mittlefehldt et al., 1998a). Pyroxene textures generally suggest very slow subsolidus cooling. Plagioclase in cumulates is more calcic (generally An_{91-95}) compared to plagioclase in basaltic eucrites, and consequently the K concentrations in cumulates are lower. Many cumulate eucrites are unbrecciated and plagioclase generally does not show zoning or shock effects. However, two of the specimens discussed below (ALH85001 and EET87548) do show signs of brecciation (Mittlefehldt et al., 1998a). As we shall see, these two cumulate eucrites also show younger Ar ages reset by later impacts.

Moama. The sample of Moama analyzed was obtained courtesy of M. Grady and the British Natural History Museum. The Ar-Ar age spectrum shows significant effects of both ^{40}Ar diffusive loss and ^{39}Ar recoil (Fig. 2a). The K/Ca ratios are considerably higher for the first several extractions, but the ^{36}Ar/^{37}Ar/^{38}Ar ratios indicate that very small amounts of adsorbed terrestrial Ar were released only in the first two extractions. The Ar-Ar age spectrum up to ~45% ^{39}Ar release resembles that expected for a sample that has lost a portion of its radiogenic ^{40}Ar by diffusion from low-temperature sites in relatively recent times (Turner, 1969). The average age of three extractions releasing ~45-78% of the ^{39}Ar and showing the same age within their uncertainties is 4.480 ±0.007 Gyr. Above 78% ^{39}Ar release, the age decreases, possibly due to gain of recoiled ^{39}Ar, although the K/Ca ratio does not show a correlated decrease. We adopt 4.48 ±0.01 Gyr as a minimum age for the time of K-Ar closure. With the reasonable assumption that these three extractions have lost little ^{40}Ar by diffusion and were not effected by ^{39}Ar recoil, 4.48 ±0.01 Gyr could also date the last closure time. Tera et al. (1997) reported for Moama a four-point Pb-Pb isochron age of 4.416 ±0.092 (some phases lay off this isochron). Jacobson and Wasserburg (1984) reported a Sm-Nd isochron age for Moama of 4.46 ±0.03 Gyr. Given their relative uncertainties, these three ages could be in agreement.

EET87520. This 52 g eucrite (weathering category B) was classified as Mg-rich and described as possessing a cumulate-like composition and Mg-rich pyroxene unlike that in diogenites (Grossman, 1994). However, the 490 ppm K concentration for our sample seems unusually high for a cumulate. The Ar-Ar age spectrum (Fig. 2b) closely resembles that expected for a sample that has lost some of its radiogenic ^{40}Ar by diffusion from low-temperature sites in relatively recent times (Turner, 1969). The ^{36}Ar/^{37}Ar/^{38}Ar ratios indicate that only the first two extractions released significant amounts of adsorbed terrestrial Ar. The overall decrease in K/Ca ratios throughout most of the extraction, followed by an increase in K/Ca above 80% ^{39}Ar release, suggests overlapping degassing of multiple mineral phases. The small decrease in age and K/Ca ratio at ~70-75% ^{39}Ar release is probably due to gain of recoiled ^{39}Ar onto the surfaces of pyroxene grains. Twelve extractions releasing ~45-100% ^{39}Ar show relatively constant ages with an average age of 4.463 ±0.020 Gyr. However, this average age may be a lower limit because of the small ^{39}Ar recoil effect and because a small amount of ^{40}Ar diffusive loss may have occurred from some of the intermediate temperature sites. If we omit the two extractions suggesting ^{39}Ar recoil (~70-75% ^{39}Ar release), then 10 extractions releasing 49% of the total ^{39}Ar define an age of 4.468 ±0.011 Gyr. An isochron plot of all 12 extractions (R^2=0.9997) gives the same age of 4.468 ±0.006 Gyr but yields a negative ^{40}Ar/^{36}Ar intercept of –24 ±29, probably caused by the small ^{39}Ar recoil effect. The last four extractions (~76-100% ^{39}Ar release) are the least likely to have been affected by Ar diffusive loss and give identical ages within their respective uncertainties. The weighed age of these four extractions is 4.473 ±0.011 Gyr. We conclude that the last K-Ar closure time for EET87520 was 4.471 ±0.011 Gyr ago.

Lugmair et al. (1991) reported variable disturbance in ages of EET87520 obtained using other isotopic chronometers. Rb-Sr was highly disturbed and no age was reported. The Sm-Nd data defined ages of 4.598 ±0.007 Gyr or 4.547 ±0.009 Gyr, depending on the specific mineral separates included in the isochron. The Pb-Pb was described as being "decidedly younger than the Sm-Nd age" but disturbed and imprecise. However, Carlson and Lugmair (2000) report a Pb-Pb age for EET87520 of 4.420 ±0.020 Gyr (and a Sm-Nd age of 4.547 Gyr).

Moore County. The Ar-Ar age spectrum for this cumulate eucrite is shown in Fig. 2c. The ^{36}Ar/^{37}Ar/^{38}Ar ratios indicate that only the first two extractions (releasing <1% of the ^{39}Ar) released significant amounts of adsorbed terrestrial Ar. The K/Ca ratio is constant except for a small K enhancement in the first few extractions and a decrease in K/Ca at ~75-89% ^{39}Ar release. This K/Ca decrease is accompanied by a decrease in Ar-Ar age and probably reflects gain of recoiled ^{39}Ar by pyroxene grain surfaces. The summed Ar age above 4% ^{39}Ar release is 4.227 Gyr. The age defined by 12 extractions releasing ~4-75% ^{39}Ar is essentially the same at 4.230 ±0.006 Gyr. If we also include in this average the three extractions releasing over ~86-100% ^{39}Ar release, the age becomes 4.235 ±0.007 Gyr.

However, ages of extractions releasing ~5-45% of the ^{39}Ar are slightly lower, suggesting a small amount of ^{40}Ar diffusive loss, and the age shown by two extractions at >89% ^{39}Ar release is slightly higher at 4.26 Gyr. For the time of last significant Ar degassing of Moore County, we adopt an age of 4.25 ±0.03 Gyr, where the error overlaps all these age combinations. Tera et al. (1997) reported for Moore Co. a six-point Pb-Pb isochron age of 4.484 ±0.019 Gyr (data for some phases lay off this isochron), and a Sm-Nd isochron (pyroxene, plagioclase, and whole rock) of 4.456 ±0.025 Gyr (95% uncertainties). Thus the Ar-Ar age of Moore County seems to have been reset more recently than these other two chronometers.

Serra de Magé. Chemically this is a cumulate eucrite, but its mineral texture is unlike most other cumulate eucrites, and after igneous formation it was metamorphosed to ~838°C (Treiman and Goldman, 2002). Our sample was received courtesy of B. Zanda and the Museum National D'Histoire Naturelle in Paris. The Ar-Ar age spectrum is shown in Fig. 2d. Although our sample contained only 42 ppm K, analytical uncertainties in calculated ages are relatively small. The $^{36}Ar/^{37}Ar/^{38}Ar$ ratios indicate that only the first two extractions released significant amounts of adsorbed terrestrial Ar. Significant diffusive loss of ^{40}Ar is shown by the first few extractions (0-8% ^{39}Ar release) from a phase with slightly higher K/Ca ratios, which suggests some concentration of K on grain surfaces. The decrease in K/Ca at ~61-70% ^{39}Ar release probably represents degassing of ^{37}Ar from pyroxene grain surfaces, but the age spectrum in this region gives no indication of ^{39}Ar recoil effects. (The larger age uncertainties for these three extractions is due to the larger applied $^{39}Ar/^{37}Ar$ corrections.) The age spectrum over ~11-100% ^{39}Ar release resembles that expected from a sample strongly, but not completely, degassed by an impact heating event <3.5 Gyr ago (Turner, 1969). Even the very retentive ^{40}Ar degassed in the 1500°C extraction (releasing ~20% of the total ^{39}Ar) gives an age of only 3.9 Gyr. Four extractions releasing ~21-45% of the ^{39}Ar have the same age within their individual uncertainties and give an average age of 3.386 ±0.007 Gyr. From these data we suggest that Serra de Magé was strongly degassed by an impact event 3.38 ±0.03 Gyr ago. The Pb-Pb age (4.399 ±0.035 Gyr; Tera et al., 1997) and the Sm-Nd age (4.41 ±0.02 Gyr; Lugmair et al., 1977) are also considerably younger than a canonical age of 4.55 Gyr.

EET87548. This 560 g eucrite (weathering category B/C) was classified as Mg-rich and described as possessing a cumulate-like composition and Mg-rich pyroxene unlike that in diogenites (Grossman, 1994). The Ar-Ar age spectrum (Fig. 2e) is relatively flat. The relatively larger uncertainties and scatter among individual ages is due to the fact that our sample contained only 19 ppm K. (Blank corrections to ^{40}Ar typically were only a few percent, and those to ^{39}Ar were even smaller. Correction for ^{39}Ar produced from Ca in the reactor is the major contributor to the error in ages.) The average age (omitting two extractions releasing very small amounts of ^{40}Ar) is 3.44 ±0.13 Gyr. If we omit the first extraction the age is 3.42 ±0.10 Gyr. (Only the first extraction suggests very small amounts of adsorbed terrestrial Ar.) We conclude that this meteorite was completely degassed by an impact event 3.4 ±0.1 Gyr ago.

ALH85001. This 212 g eucrite (weathering category A/B) was classified as Mg-rich and described as having a cumulate-like composition and Mg-rich pyroxene unlike that in diogenites (Grossman, 1994; Warren and Ulff-Moller, 1999). The Ar-Ar age spectrum is given in Fig. 2f. (The $^{39}Ar/^{37}Ar/^{38}Ar$ ratios indicate that only the first two extractions released significant amounts of terrestrial Ar.) Also shown in Fig. 2f is the relative rate of release of ^{39}Ar as a function of temperature, and this defines two distinct peaks at ~39% and ~83% of the ^{39}Ar release. This curve indicates two distinct K-bearing phases (which could represent two different grain-size populations of feldspar) and offers a reasonably explanation for the peculiar shape of the age spectrum. We interpret the age spectrum over ~2-55% ^{39}Ar release as a diffusion loss profile from the first K-bearing phase, and the age spectrum over ~55-100% ^{39}Ar release as a separate diffusion loss profile from the second phase. The age spectrum for this second, higher temperature phase shows a smaller amount of recent diffusive loss of ^{40}Ar and suggests that this phase was almost totally degassed ~3.6 Gyr ago. With this interpretation, the most likely time of major impact degassing is given by the identical ages of 3.61 ±0.01 Gyr shown by two extractions releasing 63-83% of the ^{39}Ar. It is possible that the ages of these two extractions may have been lowered by gain of recoiled ^{39}Ar. However, it is unlikely that the time of the impact event exceeds the oldest age of ~3.7 Gyr measured at high temperature.

3.3 Brecciated Basaltic Eucrites

In addition to showing varying degrees of metamorphism (see above), basaltic and brecciated eucrites have experienced impact heating and brecciation on their parent body (Mittlefehldt et al., 1998a). Bogard (1995) summarized available Ar-Ar, Rb-Sr, and Pb-Pb impact reset ages of eucrites and concluded that most impact heating occurred over the relatively limited time interval of ~4.1-3.4 Gyr ago. Bogard (1995) suggested that this epoch constituted an impact cataclysm on the HED parent body analogous to the impact cataclysm that occurred on the moon ~3.8-4.0 Gyr ago (Tera et al., 1974). Since this review of HED impact ages, we have obtained Ar-Ar ages on several additional brecciated basaltic eucrites. Further, we report here the Ar-Ar age spectra for eucritic clasts in some howardites, for which only the derived age was presented earlier. Impact heating experienced by most eucrites probably has not been sufficient to significantly alter mineral textural evidence of an earlier period of metamorphism, as is discussed below.

Piplia Kalan. This equilibrated, monomict breccia (1996 fall) is related to main group eucrites and could represent a single lava flow or a shallow intrusive body. It gives evidence of extensive thermal metamorphism, and transecting veins of glass document a later shock event (Buchanan et al., 2000a). Piplia Kalan is the first eucrite to show evidence of excess ^{26}Mg derived from extinct ^{26}Al, which requires that melting and basalt formation occurred on the parent body within a few million years after solar system formation (Srinivasan et al., 1999). Our sample was obtained from G. Srinivasan of the Physical Research Laboratory, India. The Ar-Ar age spectrum of Piplia Kalan (Fig. 3a) clearly shows the effects of impact heating. The $^{36}Ar/^{37}Ar$ and $^{36}Ar/^{38}Ar$ ratios are relatively constant except for the first extraction, which alone shows the presence of terrestrial Ar. Higher ages for four extractions releasing ~2-30% of the ^{39}Ar are not produced by terrestrial Ar contamination, but may be the consequence of loss of reactor-recoiled ^{39}Ar. In this case, recoiled ^{39}Ar could reside in those extractions releasing at ~80-90% ^{39}Ar release, where K/Ca decreases. This suggests that the upward slope of the true age spectrum at higher extraction temperatures could be much steeper than that shown in Fig. 3a, and that the impact degassing event could be younger than the youngest measured age of 3.54 Gyr. On the other hand, the higher ages at lower extraction temperatures may be caused by trapped radiogenic ^{40}Ar mobilized by the shock event, and such "saddle-shaped" Ar age spectra are observed in some strongly shocked chondrites (Bogard and Hirsch, 1980) and some terrestrial samples (McDougall and Harrison, 1999). Isochron plots ($^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$) for Piplia Kalan seem to support the second interpretation over the first. An isochron plot of 11 extractions releasing 30-100% of the ^{39}Ar (R^2 =0.997) gives an age of 3.51 ±0.03 Gyr and a $^{40}Ar/^{36}Ar$ intercept of 34±10. An isochron plot of seven extractions releasing 30-95% of the ^{39}Ar (R^2=0.999) gives an age of 3.55 ±0.03 Gyr and a $^{40}Ar/^{36}Ar$ intercept of 11±11. These positive intercepts suggest the presence of ^{40}Ar not degassed by the impact, rather than gain of recoiled ^{39}Ar. We conclude that the impact heating occurred 3.5 ±0.1 Gyr ago, and possibly ~3.55 Gyr ago.

Piplia Kalan gives a Sm-Nd whole rock isochron age of 4.57 ±0.023 Gyr (Kumar et al., 1999) and a very old Pu-Xe age (Bhandari et al., 1998). A Rb-Sr whole rock isochron gives an apparent age of 3.963 ±0.119 Gyr (Kumar et al., 1999). The Rb-Sr age is similar to the Ar-Ar age of ~3.9 Gyr shown by three extractions releasing ~97-100% of the ^{39}Ar, but whether this age of ~3.9 Gyr represents an earlier heating event or incomplete chronometer resetting cannot be determined. The observation that Ar-Ar and Rb-Sr ages are more easily affected by shock heating than Sm-Nd and Pu-Xe ages is also seen in some other shock-heated meteorites.

Sioux County. Some controversy exists as to whether this main group eucrite is a primary partial melt, an orthocumulate, or a polymict breccia (Mittlefehldt et al., 1998b; Yamaguchi et al., 1997). The dominant lithic clast in Sioux County is a basalt or diabase, but less common gabbro clasts also exist. Several of the basalt clasts weighing ~4 g. were crushed and homogenized to obtain material for various studies (D. Mittlefehldt, pers. comm., 1997), and we analyzed a sample of this powder. The Ar-Ar age spectrum of Sioux County (Fig. 3b) clearly shows the effects of impact heating, which would be consistent with a brecciation history. Eight extractions releasing ~22-74% of the ^{39}Ar define a broad age minimum and an average age of 3.64 ±0.04 Gyr. The first extraction, with much higher K/Ca, has lost much of its ^{40}Ar. Several extractions releasing ~4-22% ^{39}Ar show higher ages. The ^{36}Ar/^{37}Ar ratios for the first 12 extractions systematically decrease by a factor of 15 and suggest the release of adsorbed terrestrial Ar. (This relatively large amount of terrestrial Ar is the result of our sample having been a powder.) When an air-Ar correction is applied using the minimum measured ^{36}Ar/^{37}Ar ratio (see Garrison et al., 2000), the average age of those extractions releasing ~3-74% ^{39}Ar becomes 3.57 ±0.08 Gyr. However, an isochron plot of those six extractions releasing ~4-22% ^{39}Ar gives an age of 3.19 ±0.08 Gyr and a trapped ^{40}Ar/^{36}Ar intercept of 282 ±21, which is in agreement with the terrestrial atmospheric ratio. This isochron age is younger than the minimum in the measured age spectrum and suggests some diffusive loss of ^{40}Ar at lower temperature. It is also possible that some ^{39}Ar recoil loss has occurred, and the slight drop in age at ~85-92% ^{39}Ar release (where a decrease in K/Ca suggests pyroxene starts to degas Ar) may reflect gain of recoiled ^{39}Ar. Although the time of major impact heating of Sioux Co. is uncertain because of the significant terrestrial Ar component, it is unlikely to have occurred prior to 3.64 Gyr ago and probably occurred 3.5-3.6 Gyr ago. Tatsumoto et al., 1973) reported a Pb-Pb age for Sioux Co. of 4.526 ±0.01 Gyr, which is similar to the Ar-Ar age of the 1400°C extraction.

Asuka-87272. This 5.7 kg eucrite is a monomict breccia consisting of coarse pyroxene and plagioclase grains set in a finer-grained ground mass, which has been recrystallized to a granulitic texture (Takeda et al., 1997). The composition of the pyroxenes resembles that of ordinary eucrites, but the possible inversion to orthopyroxene suggests extensive metamorphism. The Ar-Ar age spectrum (Fig 3c) indicates extensive resetting by impact heating. Overall the age spectrum suggests a modest amount of recent diffusive loss of ^{40}Ar but the shape is distorted because of the accidental overheating of the 1075°C extraction (41-87% ^{39}Ar release). None of the extractions suggest a significant release of adsorbed terrestrial Ar, and no obvious ^{39}Ar recoil effects are observed (although the slightly higher ages at ~15-32% ^{39}Ar release may be due to ^{39}Ar recoil loss). The last four extractions (releasing ~94-100% of the^{39}Ar) give ages of 3.60-3.65 Gyr, which may be an upper limit to the time of impact heating.

Macibini. This fragmental, polymict eucrite breccia (1936 fall) was described by Buchanan et al. (2000b). The clasts display a variety of postcrystallization metamorphism, and some clasts are impact-melt breccias with a devitrified groundmass. The sample we analyzed (obtained from P. Buchanan) was largely impact glass (incorporating some melt matrix) from one of these impact-melt breccias. The Ar age spectrum (Fig. 3d) is complex and may indicate that two or more heating events are recorded in the sample. Ar degassing ages between ~3.7 and ~4.2 Gyr are suggested, but specific degassing events cannot be uniquely identified.

3.4 Howardites

We also have analyzed several eucritic clasts extracted from a few Antarctic howardites. One (QUE94200) was analyzed recently, but several Elephant Moraine samples were analyzed during the period 1990-92. Based on chemical composition, Mittlefehldt and Lindstrom (1991) suggested that these EET meteorites contained ~15-35% diogenetic component. Because howardites are brecciated mixtures of eucritic and diogenitic material originating from different depths within the parent body, they have obviously experienced multiple impacts. One purpose of these studies was to compare reset Ar ages of eucrites with those of individual howardite clasts. These samples also showed varying degrees of terrestrial weathering. The Ar-Ar data for EET howardites discussed below have not been reported in detail. A few of the ages reported here differ slightly, but not significantly, from those used by Bogard (1995).

QUE94200,13. This is a 165 g howardite (weathering class A/B), from which we analyzed a clast consisting of pyroxene phenocrysts set in a fine-grained groundmass of pyroxene and plagioclase (Mittlefehldt & Lindstrom, 1998). This clast has a bulk composition intermediate between howardites and polymict eucrites, and it may represent an impact melt of a trace-element-rich polymict eucritic target rock (Mittlefehldt & Lindstrom, 1998). The Ar-Ar age spectrum (Fig. 4a) over ~0-52% ^{39}Ar release indicates modest amounts of diffusive loss of ^{40}Ar, possibly caused by weathering. A small decrease in age where the K/Ca falls sharply (~85-95% ^{39}Ar release) suggests gain of recoiled ^{39}Ar, and the higher age seen in the third extraction (~2-11% ^{39}Ar release) may be the source of this recoiled ^{39}Ar. (The ^{36}Ar/^{37}Ar/^{38}Ar ratios are relatively flat across all extractions and indicate that only the first extraction released measurable amounts of terrestrial Ar.) The approximate time of impact degassing is probably given by two extractions releasing ~53-83% of the total ^{39}Ar, which give the same age of 3.71 ±0.01. We assign a degassing age of ~3.7 Gyr.

EET87509. We analyzed three clasts from this meteorite. Clast Q (,24) shows skeletal phenocrysts in a fine-grained groundmass; Clast D (,71) is very fine-grained and has a texture indicative of rapid cooling with no evidence of subsequent annealing; Clast E (,74) is porphyritic in a fine-grained groundmass (Buchanan & Reid, 1990; 1991). The clasts show varying degrees of quench textures, some suggesting rapid cooling, and the matrix contains glass fragments (Buchanan Lindstrom, Mittlefehldt, 1999). Buchanan et al. (1999) suggested that the matrix contains <10% diogenitic material and that the meteorite should be classified as a polymict eucrite.

The Ar-Ar age spectra for three different eucritic clasts, 24, 71, and 74, are given in Figs. 4b, 4c, and 4d, all to the same age scale. All three clasts have been impact degassed. The age spectrum for EET87509,24 shows a step in age at ~58% ^{39}Ar release. This step correlates with a decrease in K/Ca ratio and with evidence from the rate of release of ^{39}Ar for distinct K-bearing phases. The ^{36}Ar/^{37}Ar ratios suggest that only the first extraction released significant amounts of terrestrial ^{40}Ar. The age of 7 extractions releasing ~1-58% of the ^{39}Ar is 4.059 ±0.016 Gyr, and the age of three extractions releasing ~58-99% of the ^{39}Ar is 4.144 ±0.013 Gyr. The lower age plateau may itself consist of two separate age plateaus of 4.043 ±0.014 (1-17% ^{39}Ar release) and 4.067 ±0.011 Gyr (17-58% ^{39}Ar release). We conclude the time of most recent heating of this clast was 4.05 ±0.02 Gyr ago. The older plateau age at higher extraction temperatures may represent an early heating event or incomplete ^{40}Ar degassing during the ~4.05 Gyr event.

The Ar age spectrum for EET87509,71 (Fig. 4c) shows a similar degree of degassing. The average age for 8 extractions releasing 4-99% of the ^{39}Ar is 4.013 ±0.025 Gyr. We offer three possible interpretations for this age spectrum and the separate, upward slope in age over ~4-58% ^{39}Ar release and ~58-99% ^{39}Ar release. First, extractions releasing 58-89% of the ^{39}Ar may contain small amounts of recoiled ^{39}Ar, which originated from extractions releasing <18% ^{39}Ar. This explanation suggests that the time of last impact heating was 4.0-4.1 Gyr ago. Secondly, these separate age slopes may represent small amounts of ^{40}Ar diffusion loss over time, possibly caused by terrestrial weathering, from distinct K-bearing domains degassing at different extraction temperatures (c.f. Fig. 2f). This explanation also implies that the last time of impact degassing was ~4.0-4.1 Gyr ago. Thirdly, the age slopes may have been produced by severe but not quite complete Ar loss during impact heating ~3.9-4.0 Gyr ago. Thus, we adopt an impact degassing age of 4.0 ±0.1 Gyr for clast 71. This age could be identical to that derived for clast 24.

The first extraction of EET87509,74 shows significant ^{39}Ar release, a relatively large K/Ca ratio, and an apparent age of ~0.7 Gyr (Fig. 4d). These observations suggest some K was mobilized during terrestrial weathering and deposited on grain surfaces. Atmospheric ^{40}Ar corrections were applied to the first few extractions (0-30% ^{39}Ar release). The resulting Ar age spectrum indicates partial ^{40}Ar degassing from an initial age of >4.3 Gyr, with an age plateau suggested at intermediate temperatures. Four extractions releasing ~15-51% of the ^{39}Ar have similar ages, give an average age of 3.90 ±0.01 Gyr, and may define the time of last impact degassing for this clast. Given the complexity of the age spectrum, the Ar degassing age of this clast may or may not be different from the other two EET87509 clasts.

EET87531,21. This sample derived from a large eucritic clast (J), which appears moderately recrystallized and contains inhomogeneous pyroxenes (Buchanan and Reid, 1991). Buchanan et al. (1999) concluded that EET87531 is paired with EET87509. The Ar age spectrum for our sample (Fig. 4e) suggests a ^{40}Ar degassing profile from an initial age of >4.3 Gyr. (The ^{36}Ar/^{37}Ar ratios indicate that only the first extraction released significant terrestrial Ar.) Five extractions releasing ~3-57% of the ^{39}Ar give an average age of 3.81 ±0.03 Gyr, and three extractions releasing ~14-55% of the ^{39}Ar gives an age of 3.817 ±0.010. We conclude that the time of the last impact degassing of this clast occurred at 3.81 ±0.05 Gyr. This degassing age is likely distinct from that determined above for EET87509,24.

EET87503. Buchanan et al. (1999) suggested that this meteorite is a howardite and is paired with EET87513. Nyquist et al. (1994) reported concordant Rb-Sr and Sm-Nd isochron ages of ~4.5 Gyr for one clast from EET87513. However, these isotopic systems for clast EET87503,53 were severely disturbed, although apparently not by terrestrial weathering. Our Ar-Ar age for clast EET87503,53 (Fig. 4f) indicates extensive impact heating. (The ^{36}Ar/^{37}Ar/^{38}Ar ratios indicate that only the first extraction released significant terrestrial Ar.) Four extractions releasing ~31-76% of the ^{39}Ar give the same age within their uncertainties and an average value of 3.682 ±0.008 Gyr. Slightly higher ages for three extractions releasing ~2-31% of the ^{39}Ar and slightly lower ages for two extractions releasing ~76-87% of the ^{39}Ar are likely caused by ^{39}Ar recoil redistribution. The total age (all extractions) is 3.74 Gyr, and the age for ~2-95% ^{39}Ar release is 3.70 Gyr. We conclude that the time of impact degassing of this clast occurred at 3.70 ±0.03 Gyr ago, with a most probably time of 3.68 Gyr.

The Ar age spectrum for clast EET87503,23 (Fig. 4g) is very different from that for clast 53, which implies different thermal histories. Extractions releasing <65% of the ^{39}Ar show major losses of ^{40}Ar. However, five extractions of clast 23, releasing ~65-100% of the ^{39}Ar, show nearly the same age and give an average value of 4.407 ±0.013 Gyr. The ^{36}Ar/^{37}Ar/^{38}Ar ratios are relatively constant throughout the extraction and indicate that the elevated ages over ~0-16% release are not due to adsorbed terrestrial Ar. No obvious evidence exists for ^{39}Ar recoil redistribution. We suggest that this clast has experienced two degassing events. One occurred ~4.407 Gyr ago; and a second, less severe degassing occurred much more recently and affected only low and intermediate temperature sites. The second degassing event for clast 23 probably occurred on the parent body prior to breccia assembly. This second event only degassed ^{40}Ar from high diffusion sites, and rapid cooling trapped some of this mobilized ^{40}Ar. Similar "saddle-shaped" Ar age spectra are observed in strongly shocked chondrites and in some terrestrial samples containing excess ^{40}Ar (Bogard and Hirsch, 1980; McDougall and Harrison, 1999).

4. DISCUSSION OF AGES OF CUMULATE AND UNBRECCIATED EUCRITES

4.1 Age Comparisons

A summary of available radiometric ages of cumulate and unbrecciated eucrites is given in Table 1. All such ages ≥4.3 Gyr reported here are compared in Fig. 5. We also plot the Ar-Ar age of 4.48 ±0.03 Gyr reported for a clast from howardite Y-7308 (Kanoeka, 1981), which is the only additional "precise" Ar-Ar age of >4.3 Gyr of which we are aware. The ^{39}Ar-^{40}Ar ages of unbrecciated and cumulate eucrites having an age greater than ~4.3 Gyr cluster within a narrow age range of ~4.46-4.51 Gyr. Six such meteorites with relatively small and overlapping Ar-Ar age uncertainties (Ibitira, EET90020, QUE97053, Moama, and EET87520) define an age of 4.48 ±0.01 Gyr. The higher temperature plateau age of GRA98098 is consistent with this age cluster, whereas the age of PCA82502 (4.506 Gyr) is slightly older. Further, the Ar-Ar ages of the four other meteorites (Caldera, A-881467, PCA91007, and Y-7308) could well be consistent with an age of 4.48 ±0.01 Gyr, given their larger uncertainties. Five eucrites (GRO95533, QUE97014, Serra de Magé, EET87548, and ALH81005) give much younger Ar-Ar ages (Table 1), and these probably have been reset by later impact heating. The Ar-Ar age of Moore Co. also may have been reset by impact heating. These impact reset ages will be discussed in section 5.

In contrast to the Ar-Ar ages, available Pb-Pb and Sm-Nd isochron ages of unbrecciated and cumulate eucrites show a wider distribution for a smaller number of dated meteorites and range from ~4.4 Gyr up to ~4.55 Gyr (Table 1 and Fig. 5). Some of these ages have larger uncertainties compared to the Ar-Ar ages, but the reported experimental uncertainties alone do not seem sufficient to explain the wider range in these ages. Individual ages for a specific meteorite do not always agree. For some meteorites the Ar-Ar age is within combined uncertainties of either the Pb-Pb age (Caldera, Moama) or the Sm-Nd age (EET90020, Ibitira, Moama). For only two eucrites (Moore County, Serra de Magé) is the Ar-Ar age younger than both the Pb-Pb and Sm-Nd age, and the much younger Ar-Ar age of Serra de Magé was almost certainly reset by later impact heating. Only for EET87520 does the Ar-Ar age appear older than the Pb-Pb age (within mutual uncertainties). The Pb-Pb ages are apparently younger than the Sm-Nd ages for two eucrites (EET87520, and Caldera), and in no case is a Pb-Pb isochron age older than a Sm-Nd age (within mutual uncertainties). Further, two different laboratories reported a range of possible ^{147}Sm-^{143}Nd

ages for Ibitira, although the ^{146}Sm-^{142}Nd decay system in both studies suggested an old age. Because Sm-Nd data for some minerals implied a younger age, Nyquist et al. (1999) suggested metamorphism of Ibitira at the time of the Ar-Ar age.

The parent bodies of many meteorites, including HEDs, formed prior to 4.55 Gyr ago and probably ~4.56 Gyr ago. Evidence for this comes from the existence in meteorites, including a few eucrites; of decay products of short-lived nuclides such as ^{53}Mn, ^{26}Al, and ^{60}Fe (Carlson & Lugmair, 2000; Nyquist et al., 2001; Srinivasan et al., 2002; Shukolyukov and Lugmair, 1993), and from old radiometric ages of several meteorite types (e.g., Carlson & Lugmair, 2000; Tera et al., 1997). Further, precise Pb-Pb model ages of 4.556 ±0.006 and 4.560 ±0.003 Gyr were reported for Ibitira (Chen & Wasserburg, 1985; Manhes et al., 1987). What then is the explanation for the younger radiometric ages of unbrecciated and cumulate eucrites documented in Table 1 and Fig. 5? Bogard (1995) summarized measured ages of many eucrites (almost all basaltic breccias) and noted that almost all Ar-Ar ages and many Rb-Sr and Pb-Pb ages had been partially or totally reset ~4.1-3.4 Gyr ago. It was suggested that this resetting was the result of heating during a period of impact bombardment possibly related to the lunar impact cataclysm. However, 17 of the eucrites listed in Table 1 are classified as unbrecciated or cumulate and most show little to no textural evidence for significant impact heating. Four meteorites listed in Table 1 do give much younger Ar-Ar ages that are consistent with impact reset ages of brecciated eucrites (discussed in section 5). However, it seems reasonable to conclude that the Ar-Ar ages of the rest of the listed samples were not affected by the same impact history that reset the ages of most brecciated basalts. This does not mean that impact heating is ruled out for these samples, however. We now discuss three possible explanations for the radiometric ages of cumulate and unbrecciated eucrites: young formation, metamorphism, and impact heating.

4.2 Young Formation Ages.

One possible explanation for the distribution of younger ages of cumulate and unbrecciated eucrites shown in Fig. 5 is that these ages represent the actual formation times of these eucrites. From their study of Pb-Pb ages of cumulate and basaltic eucrites, Tera et al (1997) concluded that magmatic activity on the eucrite parent body(s) continued for nearly 150 Myr and that cumulate eucrites are tens of millions of years younger than noncumulate eucrites. They further noted that the primitive U/Pb ratios substantially differed between cumulate and non cumulate eucrites, and from this they suggested that these two types of eucrites might derive from different parent bodies. (Determination of the primitive U/Pb ratio is not usually straightforward in meteorites poor in volatile elements, and it is sensitive to terrestrial contamination. Extensive analyses of both leaches and residues indicated the presence of terrestrial Pb contamination in these eucrites, but the authors argue that this terrestrial component was resolved.)

Arguments can be made against different formation times and separate parent bodies for cumulate and basaltic eucrites. The strong Ar-Ar age cluster at ~4.48 Gyr (Fig. 5) is comprised of several unbrecciated, basaltic eucrites and two cumulate eucrites, which have identical Ar ages. Also, Blichert-Toft et al (2002) measured ^{176}Lu-^{176}Hf data for whole-rock samples of several cumulate and basaltic eucrites and found them to lie on a common isochron. Their conclusion was that "cumulates Moore County, Serra de Magé, and Moama do not seem to be younger than the basaltic eucrites". Further, Tera et al (1997) noted that a whole rock Pb-Pb isochron of their three cumulate eucrites defined an age of 4.483 ±0.057 Gyr, which is identical to the average value of the Ar-Ar age cluster. Thus, if cumulate and basaltic eucrites derive from different parent bodies, they must have produced cumulate and basaltic eucrites at about the same time, a time that is younger than the formation age of most other meteorite types. Although some other meteorite types give evidence for extensive metamorphic heating, no compelling evidence exists for formation of such asteroidal meteorites at times <4.5 Gyr.

Production of eucrites over a relatively long time period of ~150 Myr would imply either an extended source of heat beyond that produced by short-lived nuclides such as ^{26}Al, or very deep burial in the parent body so as to retain that heat for a significant time. Although late formation of cumulate eucrites at depth may be less of an issue, basaltic eucrites formed as surface flows or as shallow intrusive bodies, which were later metamorphosed (Stolper, 1977; Taylor et al., 1993; Takeda & Graham, 1991). In their thermal modeling of the HED parent body, Ghosh and McSween (1998) concluded that, assuming initial heating from short-lived nuclides and a parent body the size of 4 Vesta, it was possible to keep the mantle hot for ~100 Myr, sustain volcanism for this time period, and thereby explain the observed difference in ages between cumulate and noncumulate eucrites. But, if unbrecciated basaltic eucrites also formed ≤4.5 Gyr ago, does that imply that brecciated and unbrecciated basaltic eucrites have different formation times, although they are not obviously different in other basic properties? Evidence for the existence of short-lived nuclides (e.g., ^{26}Al and ^{53}Mn) in some brecciated basaltic eucrites precludes their late formation. Further, if unbrecciated eucrites formed later, how do we explain the old Pb-Pb model age and ^{146}Sm-^{142}Nd age for Ibitira?

If we assume that the eucrite ages shown in Fig. 5 represent actual formation times, what were these times? The strong tendency of the Ar-Ar ages to cluster might permit all dated samples to have a common age of ~4.48 Gyr. It is not clear why Pb-Pb ages of three out of four dated cumulates should be younger than this value (including two cumulates with both Ar and Pb ages measured). Perhaps the whole rock Pb-Pb isochron age of 4.483 ±0.053 reported by Tera et al (1997) is the actual formation time and three individual meteorites have been disturbed to suggest younger Pb-Pb ages. If so, it is interesting that Ar-Ar ages, which are usually more sensitive to thermal events, were not also disturbed. The Sm-Nd age of Serra de Magé is significantly younger than 4.48 Gyr and agrees with the Pb-Pb age. However, it is possible that the impact event at ~3.4 Gyr that reset the Ar-Ar age of Serra de Magé also disturbed the Pb-Pb and Sm-Nd age (see later discussion). Further, whereas the Ar-Ar and Sm-Nd ages of Moama, EET90020, and Ibitira could be the same within their uncertainties, the Sm-Nd age for EET87520 and Caldera are older than the Ar-Ar and Pb-Pb ages. Thus, whereas the Ar-Ar ages could be consistent with a common formation time for several cumulate and unbrecciated eucrites, the Pb-Pb and Sm-Nd ages seem only partially consistent with a range of formation ages. We do not believe that variable formation ages is the explanation for the radiometric ages of cumulate and unbrecciated eucrites.

4.3 Metamorphism Ages.

As mentioned earlier, many eucrites have been metamorphosed to varying degrees (many ≥800°C), and cations in their pyroxenes have chemically equilibrated and/or pyroxenes have undergone equilibrium phase changes (Takeda and Graham, 1991; Yamaguchi et al., 1997). This type of metamorphism likely occurred at depth, implying relatively deep burial of even those basaltic eucrites that initially solidified at the parent body surface. Arguments can be made that this metamorphism occurred very early and was not produced during later (i.e. <4.1 Gyr) impact heating. For example, some unbrecciated eucrites with old ages that did not experience later impact heating are also metamorphosed; e.g., Ibitira and EET90020 show metamorphic grade #5 on a scale of 1-6, where 6 is greatest (Takeda and Graham, 1991). Further, a pristine, unmetamorphosed clast from basaltic breccia Y-75011 did have its Ar-Ar age largely reset by impact ~3.95 Gyr ago, indicating that heating sufficient to reset Ar-Ar did not produce pyroxene metamorphism (Takeda et al., 1994; Bogard & Garrison, 1995). What then was the heat source that metamorphosed basaltic eucrites? Takeda (1979) and Ikeda and Takeda (1985) suggested that the parent body produced a magma ocean that crystallized into layers corresponding to the various metamorphic grades, with diogenites and cumulates near the bottom and low metamorphic grade basaltic eucrites near the top. Nyquist et al. (1986) suggested metamorphism occurred from the heat produced by large impact craters. Yamaguchi et al (1996; 1997) suggested that magmatic production of basalts on the parent body was so rapid that it produced a crust 15-25 km deep in a time period of only ~1 Myr, and that metamorphism occurred when basalt came into the high thermal gradient existing at depth. Very early metamorphism times would be required by the first and third models.

If early eucrite metamorphism occurred at depth, the material likely remained hot for some considerable period of time. If the surface of the parent body was heavily brecciated into a megaregolith, heat loss would be considerably retarded (Warren et al., 1991). In their thermal modeling of the differentiation of 4 Vesta, Ghosh and McSween (1998) concluded that after 100 Myr much of the interior would remain above 1100°C, and the upper ~15 km would remain above 400°C. Such a thermal environment could permit isotopic chronometers to remain open for a considerable period of time and thus many ages could be younger than ~4.55 Gyr. As various eucrites would reside at different depths and temperatures, one might also expect cumulate eucrites to show younger ages than unbrecciated basaltic eucrites. Although the data base is sparse, the Pb-Pb and Sm-Nd ages in Fig. 5 might suggest such an age difference. Also, given the common observation that Ar-Ar is most easily reset by heating and Sm-Nd the least, this model might predict the Sm-Nd ages to be older than the other ages. Caldera and Moore County do show the expected age sequence of Nd>Pb>Ar.

Some additional data also suggest that isotopic chronometers closed at different times for various eucrites. The ^{244}Pu-fission-Xe ages for ~22 eucrites vary by ~100 Myr, from ~4.56 Gyr to ~4.46 Gyr (Shukolyukov and Begemann, 1996; Miura et al., 1998). The approximate Pu-Xe ages for two cumulate eucrites (Binda and Moore Co.) are 4.53 and 4.55 Gyr, and for three unbrecciated eucrites (Ibitira, PCA82502, and Caldera) are 4.56, 4.56, and 4.51 Gyr. (These Pu-Xe ages are calculated assuming that the Angra dos Reis angrite has quantitatively retained fission Xe over its Pb-Pb age of 4.5578 Gyr.) The Pu-Xe age for Moore Co. is older than any of the other radiometric ages for Moore County (Table 1), the Pu-Xe age for Ibitira is similar to the Pb-Pb model age and one of two Sm-Nd age determinations, and the (somewhat uncertain) Pu-Xe age for Caldera could be consistent with its Ar, Pb, and Sm ages. Both of these Pu-Xe investigations concluded that parent body metamorphism is a likely explanation for the younger Pu-Xe ages. It is difficult to predict how easily Pu-Xe would be reset during metamorphic heating at depth. Although Xe is a gas, it diffuses less readily than Ar, and greater pressure at depth might enhance its retention in minerals, even when elements like Pb and Nd undergo isotopic exchange. For several brecciated basaltic eucrites showing Pb-Pb ages considerably younger than 4.55 Gyr, Shukolyukov and Begemann (1996) noted that the Pu-Xe ages were considerably older than the Pb-Pb ages, indicating a greater resistance to resetting during impact heating. These authors also noted that for most of these eucrites, Pu-Xe ages correlated with K-Ar and Ar-Ar ages, although the Ar-Ar ages were much younger and indicated a much greater ease of diffusion loss of Ar compared to Xe during shock heating.

To summarize, it appears that retention of considerable heat from early decay of short-lived nuclides might permit the formation of basaltic or cumulate eucrites at times considerably later than formation of the parent body >4.555 Gyr ago. On the other hand, the presence of short-lived nuclides observed in some eucrites, along with the nature of likely models needed to produce the observed metamorphism in many basaltic eucrites, require that they formed very early, i.e., >4.55 Gyr ago. If early metamorphism left eucrites in a hot environment at depth, their isotopic chronometers may have remained open for significant and variable periods of time. This might permit, in principle, an explanation for the apparent variation in ages among different eucrites and for different ages obtained by different chronometers for the same or similar eucrites, although the specific ages are not always what is expected. However, one difficulty with this scenario is the strong clustering of Ar-Ar ages of both cumulate and unbrecciated eucrites at ~4.48 Gyr. Ar-Ar ages are expected to be the easiest to reset by metamorphic heating, and thus we would expect them to give the youngest values. Further, if variable Pb-Pb and Sm-Nd ages among these eucrites reflect slow cooling and different closure times, why do the Ar-Ar ages also not show greater variations among meteorites? Thus, we reject this scenario as the total explanation of eucrite chronology and examine the possible role of early impact heating.

4.4 Impact-Produced Ages.

We conclude that the strong clustering of Ar-Ar ages of both cumulate and unbrecciated eucrites (Fig. 5) is not accidental, but rather dates some major, widespread event on the HED parent body. In their multidiscipline study of EET90020, Yamaguchi et al (2001) concluded from mineral textures that this unbrecciated eucrite formed at the surface and later was metamorphosed at depth to grade 5. It was then briefly heated above the subsolidus temperature of ~1060°C, causing partial melting, followed by rapid cooling of several °C/day. The temperature of the rock just prior to this reheating could have been ~870°C, based on the two-pyroxene method. These authors suggested that this partial melting event was responsible for resetting the Sm-Nd and Ar-Ar ages (Table 1), as well as apparent disturbance of the Rb-Sr and Mn-Cr systems. They further suggested that this reheating event was the formation on Vesta of a very large impact crater ~4.50 Gyr ago, which excavated relatively hot material from considerable depths and caused it to quickly cool. Miyamoto et al. (2001) suggested a similar history for Ibitira.

Vesta presents several lines of evidence for early impact heating events that could have affected eucrite chronology. Study of Vesta using the Hubble Space Telescope indicates the existence of a few very large craters (Thomas et al., 1997). The largest crater near Vesta's south pole is ~460 km in diameter and ~13 km deep below the rim, and contains a central peak nearly as high. A second crater is

~160 km in diameter and ~6 km deep. Spectral studies suggest that, whereas much of Vesta's surface resembles howardites or basaltic eucrites, other areas likely associated with large impact structures suggest enrichment in pyroxene and/or olivine, and may indicate exposure of Vesta's lower crust or mantle (Gaffey, 1997; Thomas et al., 1997). Vesta also has a dynamical family of ~149 small asteroids, which are closely associated with it physically, and which are thought to have derived from a large collision with Vesta (Zappala et al., 1995). This Vesta family may have been ejected from one of these large craters (Sykes and Vilas, 2001). In addition, observers have identified ~38 Vestoids, which are small (~4-10 km) asteroids with Vesta-like spectra and whose orbits form a bridge connecting Vesta with the ν_6 resonance and the 3:1 Kirkwood gap (Binzel and Xu, 1993). These Vestoids also may have been ejected from one of the large craters on Vesta. The orbital location of Vesta does not favor direct ejection of material to Earth. Gravitational perturbations by Jupiter from the ν_6 resonance and the 3:1 Kirkwood gap are thought to be "gates" through which objects pass on their way to Earth (Wisdom, 1985; Binzel & Xu, 1993; Wetherill 1985). Thus, it is likely that eucrites in our collections originally derived from one or more large impacts on Vesta (or a similar body now disrupted) and were brought to Earth by further collisions on one of these smaller, secondary asteroids (Sykes and Vilas, 2001).

We suggest that one of these very large impact events on Vesta occurred ~4.48 Gyr ago and excavated both basaltic and cumulate eucrites (and probably diogenites) from considerably depths. At the time of excavation, the temperature of most ejecta was above the closure temperature of the K-Ar chronometer. Rapid cooling immediately after the impact event produced closure of all isotopic chronometers, including all K-Ar ages. Older Sm-Nd and Pb-Pb ages for two dated meteorites can be explained if their ambient temperature had fallen sufficiently low prior to the impact that these chronometers had already closed – e.g., both the Sm-Nd and Pb-Pb ages of Caldera and the Sm-Nd age of EET87520. (Early closure might also account for the slightly older Ar-Ar age for PCA82502.) Sm-Nd and Pb-Pb ages of ~4.46-4.51 Gyr for some other eucrites are sufficiently imprecise that they also could have closed during rapid cooling after impact ejection 4.48 Gyr ago. The younger Pb-Pb ages for two cumulates, Moama and EET87520, may require some additional explanation, although the uncertainty in the Pb-Pb age for EET87520 (±92 Myr) more than overlaps the postulated ~4.48 Gyr impact heating event. Another consideration in interpreting isotopic ages for slowly cooling systems, such as the Vesta crust prior to the ~4.48 Gyr impact, is that different minerals may close to diffusion at different times. If, as postulated for EET90020, the impact event then imparted additional, sudden heating, Pb-Pb and Sm-Nd isochrons defined by mineral phases may partially reflect different closure times and differential disturbance, rather than a true age. A similar kind of age disturbance was demonstrated for Rb-Sr and

Sm-Nd ages of a lunar rock heated in the laboratory to temperatures up to 990°C for a time period of 170 hours (Nyquist et al., 1991). Further, in the various Pb-Pb isochrons for Moama (Tera et al., 1997), the whole rock, plagioclase, and pyroxene acid-treated samples that define the isochron are not completely linear. Thus, we suggest that those few ages in Fig. 5 that appear to be significantly younger than ~4.48 Gyr are not true closure ages.

Another question about the chronology of cumulate and unbrecciated eucrites is why their ages were not reset in the later cataclysmic bombardment that reset Ar-Ar ages of most brecciated eucrites (see section 5). One explanation might be statistical in that a few basaltic eucrites simply escaped such resetting, whereas ages of a few cumulate eucrites were later reset (Table 1). A second possible reason could be that these meteorites remained deeply buried inside Vesta during this bombardment. This explanation seems incompatible with the ~4.48 Gyr event scenario postulated above, however, and would still require large impact events to uncover these eucrites from depth. The younger Pb-Pb and Sm-Nd ages (4.40-4.41 Gyr) for Serra de Magé may date resetting in a later impact event, and evidence presented in section 5 argues for major impact events in the range of ~3.4-4.1 Gyr. A third possible explanation for the lack of brecciation among some eucrites is that a very large impact ~4.48 Gyr ago ejected the direct parent objects of cumulate and unbrecciated eucrites away from Vesta as km-sized Vestoids or the associated dynamical Vesta family. These smaller direct parent objects cannot suffer the large impacts necessary to heat crater ejecta sufficiently to reset isotopic ages without destroying the parent asteroid (Bogard, 1995). Thus, cumulate and unbrecciated eucrites might derive from smaller asteroids ejected from Vesta ~4.48 Gyr ago, asteroids which did not experience later impact heating. As most brecciated, basaltic eucrites did experience later impact heating, they presumably were ejected from Vesta at later times. Because the cosmic ray exposure ages of all eucrites are much younger (<0.1 Gyr), they must have resided in bodies at least several meters in diameter for most of their history.

4.5 Time of Impact Event.

We now utilize a test to examine whether all individual, older Ar-Ar ages of eucrites are consistent with the conclusion that these ages date a single thermal event. Figure 6 is an age probability plot for 10 Ar-Ar age analysis of 9 unbrecciated and cumulate eucrites (Table 1). Each curve represents a gaussian probability distribution of an individual Ar-Ar age, assuming that the error reported for each age represents a one-sigma uncertainty in this age. (Although the error we report for each age is not strictly a 1σ statistical error, it is approximately so.) These curves are constructed from the standard formula for normal distribution of measurements about a single true value (Bevington, 1969). For each curve, the reported age uncertainty is equivalent to ~66% of the area in the middle of the curve. Consequently, a smaller age uncertainty yields a curve that is narrow in age and taller (greater probability). If two or more age probability curves overlap significantly, then they are consistent with a single heating event. In fact, with one possible exception (PCA82502), all analyses of unbrecciated and cumulate eucrites show a significant overlap in their age probability curves. The solid, heavy curve in Fig. 6 is constructed by adding together the probability of all 10 individual curves in order to give a summed probability distribution, and then dividing this curve by 10. This permits one to read the summed probability for any age, to the nearest Myr, directly from the same probability scale as the individual curves. It is obvious that this summed curve itself resembles a single probability distribution. The most probable age in this summed curve centers around 4.48 Gyr, and to the extent that the shape of this summed curve itself resembles a gaussian distribution, the one-sigma uncertainty in this most probable event age is ~±20 Myr. This evaluation constitutes strong statistical evidence that at least 9 of these 10 Ar-Ar ages can readily be explained by a single degassing event ~4.48 Gyr ago.

We applied this same probability test to the 12 Pb-Pb and Sm-Nd isochron ages (Table 1) reported for seven cumulate and unbrecciated eucrites (Fig. 7). (In this case the summed probability curve was divided by 12.) Note that the age range in this figure is more than a factor of 2 larger than that of Fig. 6.) The individual Pb-Pb and Sm-Nd age curves do not all overlap, and the summed probability curve (heavy solid line) in no way resembles a gaussian curve indicative of a single event. This indicates either that several age resetting events are required or that some of these individual meteorite ages do not represent real events. As mentioned above, we suggest that the three ages distinctly older than 4.50 Gyr represent isotopic closure during parent body cooling, and that the three ages younger than ~4.44 Gyr represent partial disturbance rather than the times of resetting events. Five other Sm-Nd and Pb-Pb ages are consistent with the Ar-Ar age distribution (Fig. 6). It is interesting to note in Fig. 7 that those three eucrites with accurately measured isochron ages of 4.516, 4.537, and 4.547 Gyr combine in the summed curve to give two peaks. However, there is no compelling reason to believe these three age distributions can be explained by two events occurring at ~4.52 and 4.54 Gyr. This illustrates the point that one must be cautious in using summed probability curves to infer times of specific events when multiple events are involved.

5. IMPACT AGES OF BRECCIATED EUCRITES

5.1 Distribution of Eucrite Impact-Reset Ages.

Bogard (1995) summarized available ^{39}Ar-^{40}Ar ages of eucrites, along with those Rb-Sr and Pb-Pb ages that are ≤4.3 Gyr. These ages gave a broad distribution, with most samples showing ages between ~3.4 and ~4.2 Gyr. Only three eucrites gave Ar-Ar ages of >4.3 Gyr and none gave Ar ages of <3 Gyr. These ages were all attributed to resetting during heating by relatively large impacts on the HED parent body, as only large craters and their ejecta deposits retain sufficient heat to cause such resetting. The existence of polymict eucrites and eucritic clasts in howardites imply multiple impact events, which would seem to be consistent with a distribution of impact ages. Bogard (1995) also noted a general similarity between the distribution of eucrite ages and Ar-Ar, Rb-Sr, and Pb-Pb ages of lunar highland rocks returned by three Apollo missions. Tera et al. (1974) suggested that resetting of these lunar rock ages was caused by an enhanced period of impact bombardment of the moon, for which they coined the term lunar cataclysm. Bogard (1995) suggested that an analogous impact cataclysm occurred on the HED parent body and throughout the whole inner solar system. The reason why widespread age resetting occurred on the moon and the HED parent, but apparently not on some other meteorite parent bodies, was attributed to the larger size of the moon and HED parent compared to other meteorite parent bodies. Larger size permitted the generation of larger and hotter impact deposits without destroying the parent object.

The new data reported here furnish 22 additional Ar-Ar ages that can be added to the 46 Ar-Ar ages compiled by Bogard (1995). The updated histogram of Ar-Ar ages of eucrites is shown in Fig. 8. As done previously, Ar ages are plotted in 0.1 Gyr increments, and more precisely determined Ar ages are distinguished from approximate Ar ages. Precise Ar-Ar ages are somewhat arbitrarily defined as those for which a specific age uncertainty is reported. These individual age uncertainties ranged over ±0.02-0.10 Gyr, but most were no greater than ±0.05 Gyr. Generally speaking, the age histogram shown by "precise" ages is similar to that of approximate Ar-Ar ages. The most obvious change in this age histogram, compared to the previous one, is the addition of several meteorites with ages of 4.50 ±0.05 Gyr. These, of course, are the unbrecciated and cumulate samples discussed earlier. These older ages measure events that occurred much earlier than the lunar cataclysmic impacts, although we argue above that they also date a single, large impact event. However, nine new Ar-Ar ages plot in the age range 3.4-3.7 Gyr, and the Moore Co. cumulate plots at 4.2 Gyr. Four of these nine new Ar ages are considered as "precise". The new distribution of eucrite impact ages below 4.4 Gyr is generally similar to that reported earlier, with a slightly greater relative weighing toward ages of <3.8 Gyr.

An age probability plot for 28 eucrite samples with reported age uncertainties and with Ar-Ar ages between 3.3 and 4.1 Gyr is shown in Fig. 9. In this case the summed probabilities (heavy curve) were divided by 7 rather than the proper 28 in order to make the shape of the curve more discernable. Thus, the summed probability for a given age read on the Y-axis should be decreased by a factor of four. This summed probability curve suggests heating events at ~3.45, 3.55, 4.0 Gyr, and possibly also at ~3.7, 4.05, and 3.8-3.9 Gyr. Seven samples give ages of ~3.95-4.05 Gyr, and seven samples give ages of ~3.45-3.55 Gyr. Only four analyses give ages in the range of 3.80-3.95 Gyr, which is the time interval in which several large lunar basins probably were formed by impact (Stöffler and Ryder, 2001).

5.2 Nature of "Cataclysmic" Bombardment"

The nature of the early lunar bombardment and whether there existed a significant short-term increase in impactor flux over the decaying background flux is still under debate (e.g., Hartmann et al., 2000; Ryder, 2002). Ryder (2002) has argued that a distinct lunar cataclysm existed and that it was characterized by a significant increase in very large impacts. He also argued that this increase may have been relatively short-lived, perhaps ~0.2 Gyr in duration, and occurred ~4.0-3.8 Gyr ago. Ar-Ar and Rb-Sr ages of highland rocks from three Apollo lunar highland sites show a broad distribution of ~3.7-4.1 Gyr (Bogard, 1995). However, good arguments have been presented that several of the younger, large impact basins on the moon formed in the narrow time interval of ~3.82-3.90 (Ryder, 2002; Stöffler and Ryder, 2001). (These basin ages were obtained by dating impact melts for which a strong argument can be made that they derived from either the Imbrium, Serenitatis, or Nectaris basins.) It is still not clear, however, whether the older (pre-Nectarian) lunar impact basins have ages of ~3.9-4.0 Gyr or are considerably older than 4.0 Gyr. In the absence of good age estimates for the older lunar basins, we cannot know for certain when an increase in flux of large impactors actually began, or even if a dramatic increase above the background flux actually occurred.

Several workers have considered possible sources of objects that might have produced a cataclysmic bombardment ≥0.5 Gyr after the moon formed. (Objects with a total mass of $\geq 10^{22}$ g are apparently required to produce the lunar basins, and the source of these objects would have to be orders of magnitude more massive still.). Suggested sources include breakup of a large body in the asteroid belt, gravitational scattering of objects near Neptune and Uranus, and perturbations of comets in the Oort cloud by close-passing stars (see Hartmann et al, 2000). Each of these suggested sources of objects implies that not just the moon, but the whole inner solar system, should have experienced this cataclysmic bombardment. Thus, evidence for impact reset ages on the relatively large Vesta asteroid could be expected.

Because much lower crater densities exist on dated mare surfaces compared to the lunar highlands, it is generally believed that by ~3.7-3,5 Gyr ago this early impactor flux, whatever its nature, had fallen to a value more comparable to the average flux over the past 3 Gyr of lunar history (Ryder, 2002; Stöffler and Ryder, 2001). The age of the youngest, large lunar basin (Orientale) is estimated at ~3.82 Gyr, and certainly is not younger than 3.7 Gyr (Stöffler and Ryder, 2001). However, the lunar rock chronology that defines the impact cataclysm is associated almost entirely with only 2-4 large and recent lunar nearside basins, primarily Imbrium and Serenitatis, and less certainly Nectaris and Crisium. The time duration of the cataclysmic bombardment involving smaller impactors that produced, not impact basins, but large lunar craters on the back side of the moon (and the largest craters on Vesta, which are much smaller than lunar basins) is still unclear. For example, 31 small impact melt clasts in four lunar meteorites (which may have originated from the lunar backside) show the wide distribution in Ar-Ar ages of ~2.4-4.1 Gyr, and fewer than half of these are older than 3.7 Gyr (Cohen et al., 2002). Those ages that are <3.7 Gyr must have been reset by the background impactor flux, not the cataclysmic bombardment, and it may be the case that few or none of the ages of these melt clasts were reset by an enhanced flux of large impactors. On the other hand, the existence of four extensive impact melt deposits, having an age of 3.47 Gyr, in South Africa and western Australia are interpreted to have formed in several large impacts of objects ~20 km in diameter (Byerly et al., 2002; Byerly and Lowe, 1994). An object of such size could be expected to produce a very large crater (possibly a small basin) on the moon or Vesta. On the moon it apparently requires a relatively large crater to significantly reset Ar-Ar ages in rocks ejected outside the crater. Thus, a crater like Copernicus did reset Ar-Ar ages of ejected material (Bogard et al., 1994), but smaller craters like those visited at various Apollo landing sites did not. (Impact melt, which largely is contained within the crater, was apparently not sampled for any of these smaller craters, but was for the Imbrium and Serenitatis impacts.)

We suggest that a cataclysmic bombardment, as described for the moon from impact reset ages of highland rocks, must meet two basic criteria: it must show an apparent increase in impactor flux compared to the decaying background flux, and this enhanced impactor flux must later decrease into the background flux. The distribution of impact reset ages for eucrites (Figs. 8 & 9) appear to satisfy both of these criteria. The lunar impact cataclysm (assuming it existed) as measured by formation times of large basins began at an unknown time >3.9 Gyr ago and lasted until ~3.8 Gyr ago. The Vesta cataclysm (again assuming the term applies) appears to have begun ~4.1 Gyr ago and lasted until ~3.4 Gyr ago. Fewer eucrite ages occur in the time interval of 4.1-4.4 Gyr than in the interval 4.0-3.4 Gyr. This observation is consistent with the lunar impact cataclysm, as its upper time bound is not well constrained. On the other hand, impact reset ages of eucrites in the time interval of 3.4-3.7 Gyr appear to be at least as numerous as those in the interval 3.7-4.0 Gyr. Whether we consider only "precise" Ar-Ar ages or both precise and approximate ages, the distribution is continual across 4.3-3.7 Gyr, but suggests an enhancement at ~4.0 and ~3.5 Gyr. Thus, the distribution of impact reset ages of eucrites (Fig. 8) shows a broader range than that postulated by Ryder (2002) for the lunar cataclysm and may be in conflict with the lunar observation that the impact cataclysm flux had fallen to the background flux level by 3.7-3.5 Gyr ago, and that no large lunar basins formed after~3.8 Gyr ago. However, the enhanced number of reset eucrite ages at ~3.4-3.5 Gyr is consistent with the evidence for several large impacts on Earth 3.47 Gyr ago (Byerly et al., 2002).

We can offer three possible explanations for the difference in distribution of impact reset ages between eucrites and lunar highland rocks. One is that the timing of the bombardment on Vesta somehow lasted longer than that on the moon, although it is difficult to explain why this should be the case. Secondly, the late stages of the bombardment may have consisted of smaller impacting objects than those which formed the lunar basins, and these smaller impactors may have persisted in the inner solar system until ~3.4 Gyr ago. Presumably the flux of later arriving objects was not high, or we would observe more ages of <3.7 Gyr among lunar highland rocks. A third and related explanation is the possibility that both eucrites and returned lunar highland rocks represent an incomplete sampling of the full range of reset ages on these bodies. Above we suggested that the cluster of ages at ~4.48 Gyr for unbrecciated and cumulate eucrites may represent resetting by the largest crater observed on Vesta. Possibly two other large craters on Vesta formed at times of ~4.0 and ~3.5 Gyr and caused resetting of many of the basaltic eucrite ages. Lunar highland rocks were all returned from a limited area of the moon, and many of these had their ages reset by three large impacts (Imbrium, Serenitatis, and Crisium, out of ~30 recognized large basins) that occurred in this same area of the moon. The distribution of ages of large impactors across the whole surface of the moon is not accurately known. In any case, both the lunar and eucrite ages indicate that after ~3.4 Gyr ago, large scale impact heating apparently ceased on both bodies. Clearly our understanding of the nature of the early bombardment of the inner solar system by relative large objects remains incomplete.

6. VESTA'S THERMAL HISTORY

Similarities in spectral signatures between the asteroid 4 Vesta and eucritic meteorites suggest that Vesta may be the original parent body of eucrites (McCord et al., 1970). Two groups of much smaller asteroids may have been derived from Vesta by past impacts. One group consists of a large family with orbital parameters related to those of Vesta (Zappala et al., 1995). The other group, Vestoids, show similar spectra to Vesta, and their distribution in space between the ν_6 resonance and the 3:1 Kirkwood gap makes them likely direct parent objects for meteorites that fall on Earth (Binzel and Xu, 1993). Several quite large impact craters apparently exist on Vesta (Thomas et al., 1997; Gaffey, 1997). These may have been the source for the Vesta asteroid family and the Vestoids, which in turn may be the source of eucrites that fall on Earth (Sykes and Vilas, 2001 and references therein).

The eucrite parent body, which we assume to be Vesta, probably formed prior to 4.56 Gyr ago (Lugmair and Shukolyukov, 1998). Soon thereafter decay of short-lived radionuclides such as ^{26}Al (Srinivasan et al., 1999; Nyquist et al., 2001) caused extensive melting, likely core formation, and generation of large quantities of surface basalt flows. The presence of decay products of short-lived nuclides and old Pb-Pb radiometric ages for a few eucrites (e.g., Carlson and Lugmair, 2000) implies that this basalt production occurred relatively rapidly. However, modeling of the early thermal history of Vesta from decay of ^{26}Al indicates that the interior of Vesta likely remained hot for a substantial period of time. Much of the asteroid may have remained near the basaltic melting point for a time of $\sim 10^8$ years (Ghosh and McSween, 1998). Most eucrites give evidence of thermal annealing during this period, many to temperatures of $\geq 800^{o}$C (Yamaguchi et al., 1996; 1997). For example, the pyroxenes in many eucrites have been heated sufficiently so as to homogenize concentrations of cations such as Fe and Mg (Takeda and Graham, 1991). This metamorphism probably occurred soon after eucrites formed, either through formation of a deep layered crust (Ikeda and Takeda, 1985) or by rapid burial of many successive basalt flows (Yamaguchi et al., 1997). Cumulate eucrites show evidence of even greater heating than basaltic eucrites (Mittlefehldt et al., 1998a) and probably resided at greater depths.

Most eucrites are breccias formed by surface impacts and give ample evidence in their radiometric chronology for impact mixing and heating that occurred long after Vesta formed. With the reasonable assumption that eucrite metamorphism occurred at some depth in the parent body, impacts of significant size are apparently required to bring these meteorites to the near-surface. However, most cumulate eucrites and a few basaltic eucrites are unbrecciated and apparently were not affected by these later impacts.. For example, 12 Pb-Pb and Sm-Nd isochron ages of four cumulate and three unbrecciated basaltic eucrites lie between ~4.4 Gyr and ~4.55 Gyr (Tera et al., 1997; Carlson and Lugmair, 2000). In contrast, we show in this work that ^{39}Ar-^{40}Ar ages of two cumulate eucrites and seven unbrecciated basaltic eucrites cluster rather tightly about an age of 4.48 Gyr. Although it was previously suggested that the younger Pb-Pb and Sm-Nd ages indicate late formation of these eucrites, possibly on separate parent bodies (Tera et al., 1997), we argue that this explanation cannot account for diverse data sets. It appears more likely that the younger ages of cumulate and unbrecciated basaltic eucrites is the result of their residence at depth in a common parent, where elevated temperatures kept isotopic systems open for times significantly after the eucrites actually formed. However, if this were the only explanation for the younger radiometric ages, we might expect to see variable ages among different meteorites, but we would also expect to see Sm-Nd ages older than Pb-Pb ages, older than Ar-Ar ages, reflecting the relative ease of resetting of these radiometric chronometers. Residence at depth alone cannot explain the tight clustering of Ar-Ar ages, which appear older than a few Pb-Pb ages.

Thus, we suggest that the distribution of radiometric ages of cumulate eucrites and unbrecciated basaltic eucrites (Fig. 5) has two related explanations. These samples did reside under elevated temperatures at depth for a significant time period after their formation. However, ~4.48 Gyr ago a very large impact on Vesta, possibly the one that formed the largest (~460 km diameter) crater believed to exist on its surface, ejected these meteorites from depth and quenched their temperatures. These ejected objects may have produced the Vestoids. Because the K-Ar system was open in all meteorites, this ejection and cooling event set the Ar-Ar ages to a common value. The Sm-Nd and Pb-Pb ages of some of these eucrites were also set by the large impact ejection event. Because the Sm-Nd system closes at higher temperatures than does K-Ar, the Sm-Nd ages of some other eucrites (i.e., those with ages older than 4.48 Gyr) had already closed. The younger Sm-Nd and Pb-Pb ages, and much younger Ar-Ar age, for cumulate Serra de Magé (and the younger Ar-Ar age for Moore County) are probably due to much later impact disturbance.

Significantly later than this ~4.48 Gyr impact event on Vesta, its surface suffered additional large impacts which affected radiometric chronometers. The K-Ar ages of essentially all brecciated basaltic eucrites (and howardites) were partially or totally reset during this period, and Rb-Sr and Pb-Pb ages of some eucrites were disturbed or partially reset. Bogard (1995) suggested that the source of these impactors was related to the impact cataclysm on the moon, which reset the ages of most lunar highland rocks. This period of impact resetting on Vesta, about 4.1 to 3.4 Gyr ago, appears to have lasted later than the lunar cataclysm and apparently requires several distinct impact heating events. Parent bodies of most other meteorite types do not show the same degree of chronometer impact resetting because they were smaller than Vesta and thus could not sustain an impact of sufficient size to produce chronometer resetting. The origin and nature of these impactors and their actual flux over time remains unknown.

ACKNOWLEDGEMENTS

This research was supported by NASA's Cosmochemistry Program under RTOP 344-31.

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Table 1. ^{39}Ar-^{40}Ar, Pb-Pb and ^{147}Sm-^{144}Nd Age Summary (Gyr) of Some Eucrites.

Meteorite	Ar-Ar	Pb-Pb	Sm-Nd	Reference
Unbrecciated Basaltic				
EET90020	4.489 ±0.013 (fine-grained)		4.51 ±0.04	(a)
	4.486 ±0.008 (coarse-grained)			
Ibitira	4.486±0.016	4.556 ±0.006*	4.46 ±0.02	(b) (c)
			4.41-4.57	(d)
QUE97053	4.480 ±0.015			
GRA98098	4.45 ±0.01, 4.49 ±0.02			
PCA82502	4.506 ±0.009			
A-881388	4.480 ±0.007			
PCA91007	≥4.444			
Caldera	4.493 ±0.012	4.516 ±0.003	4.544 ±0.019	(e)
A-881467	~4.46			
GRO95533	3.55 ±0.03			
QUE97014	3.54 ±0.04			
Y-7308	4.48 ±0.03			(f)
Cumulate				
Moama	4.48 ±0.01	4.426 ±0.092	4.46 ±0.03	(g) (h)
EET87520	4.473 ±0.011	4.420 ±0.020	4.547 ±0.009	(i)
Moore County	4.25 ±0.02	4.484 ±0.019	4.456 ±0.025	(g)
Serra de Magé	3.38 ±0.03	4.399 ±0.035	4.41 ±0.02	(g) (j)
EET87548	3.4 ±0.1			
ALH81005	3.6-3.7			
Brecciated Basaltic				
Piplia Kalan	3.5 ±0.1	(Rb-Sr=3.96)	4.57 ±0.023	(k)
Sioux County	~3.55			
QUE94200	~3.7			
A-87272	≥3.6			
Macibini	~3.7-4.2			

All ^{39}Ar-^{40}Ar ages are JSC data reported herein, except that for Y-7308. The two Ar ages listed for GRA98098 are discussed in the text. Pb-Pb and Sm-Nd isochron ages are taken from the cited references.

* The Pb age for Ibitira is a model age.

References: (a) Yamaguchi et al., 2001; (b) Chen and Wasserburg, 1985; (c) Prinzhofer et al., 1992; (d) Nyquist et al., 1999; (e) Carlson and Lugmair, 2000; (f) Kanoeka, 1981; (g) Tera et al., 1997; (h) Jacobsen and Wasserburg, 1984; (i) Lugmair et al., 1991; (j) Lugmair et al., 1977; (k) Kumar et al., 1999.

FIGURE CAPTIONS

Figure 1. ^{39}Ar-^{40}Ar ages and K/Ca ratios as a function of cumulative ^{39}Ar release for unbrecciated basaltic eucrites: (a) QUE97053; (b) GRA98098; (c) PCA82502; (d) PCA91007; (e) Caldera; (f) Asuke-881388; (g) Asuka-881467; (h) GRO95533; and (i) QUE97014. Concentrations of K and Ca measured on these samples are also given.

Figure 2. ^{39}Ar-^{40}Ar ages and K/Ca ratios as a function of cumulative ^{39}Ar release for cumulate eucrites: (a) Moama; (b) EET87520; (c) Moore County; (d) Serra de Magé; (e) EET87548; and (f) ALH85001. For ALH85001 the two-phase, differential release of ^{39}Ar is also indicated. Concentrations of K and Ca measured on these samples are also given.

Figure 3. ^{39}Ar-^{40}Ar ages and K/Ca ratios as a function of cumulative ^{39}Ar release for brecciated basaltic eucrites: (a) Piplia Kalan; (b) Sioux County; (c) Asuka-887272; and (d) Macibini.

Figure 4. ^{39}Ar-^{40}Ar ages and K/Ca ratios as a function of cumulative ^{39}Ar release for eucritic clasts in howardites: (a) QUE94200; (b) EET87509,24; (c) EET87509,71; (d) EET87509,74; (e) EET87531,21; (f) EET87503,53; and (g) EET87503,23.

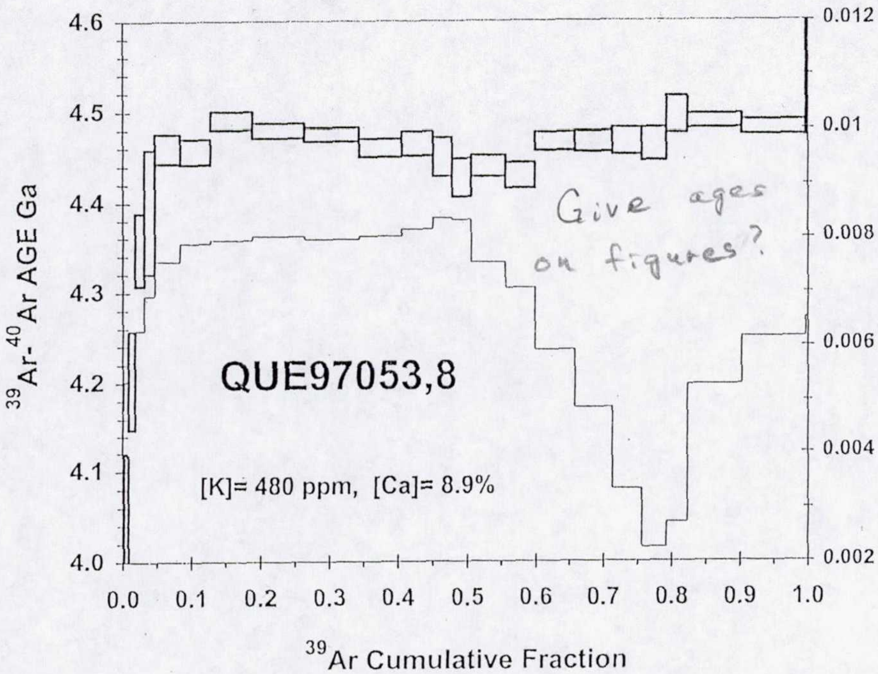
Figure 5. ^{39}Ar-^{40}Ar, Pb-Pb, and Sm-Nd ages for cumulate and unbrecciated basaltic eucrites (Table 1). All Ar-Ar ages are from JSC, except that for unbrecciated Y-7308 (triangle). Pb-Pb and Sm-Nd ages are isochron ages, except the Pb age for unbrecciated Ibitira (light-colored point), which is a model age. Two Ar-Ar ages shown as light symbols have greater uncertainties, one age is a lower limit, and the two connected points represent the two plateau ages of GRA98098.

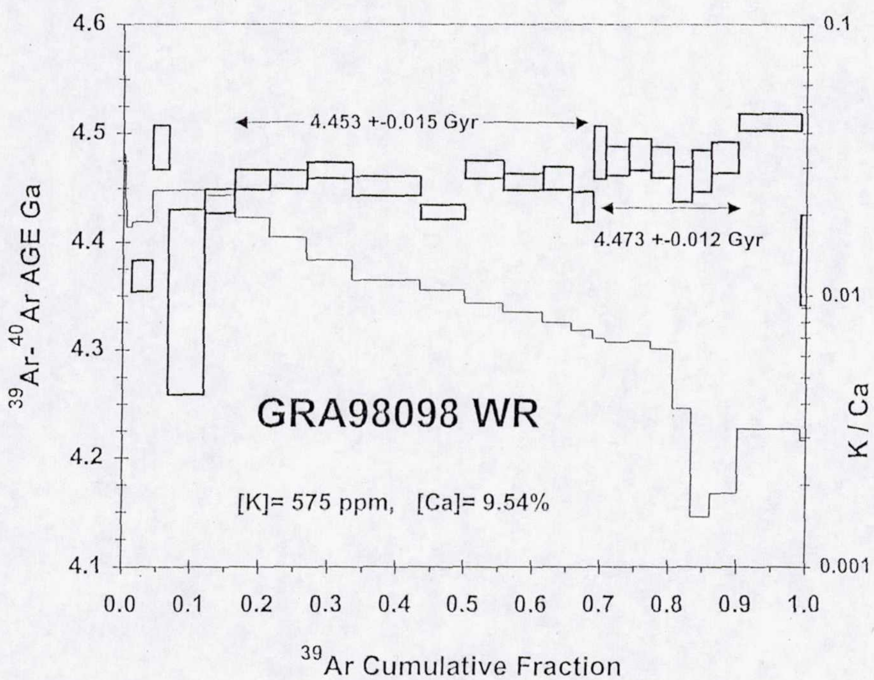
Figure 6. Ar-Ar age probability curves (gaussian) for 10 analyses of 9 cumulate and unbrecciated basaltic eucrites. The heavy-line curve is the summed age probability, which also resembles a gaussian distribution. The mean summed age is 4483 $\pm$~16 Myr.

Figure 7. Age probability curves (gaussian) for Pb-Pb and Sm-Nd isochron ages (Table 1) of seven cumulate and unbrecciated basaltic eucrites. The heavy-line curve is the summed age probability.

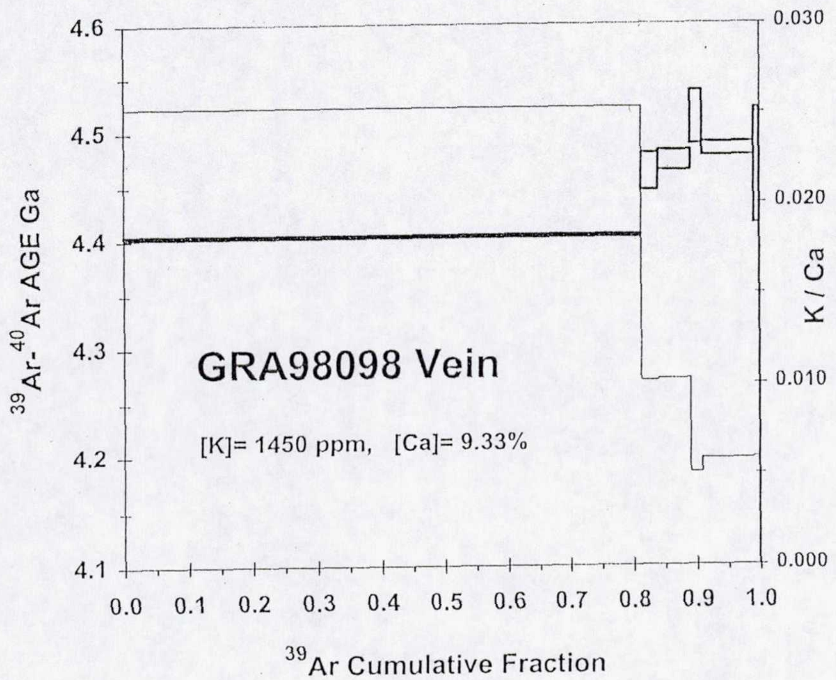
Figure 8. Histogram of Ar-Ar impact reset ages of eucrites. Rb-Sr and Pb-Pb ages of <4.3 Gyr are also shown.

Figure 9. Ar-Ar age probability curves (gaussian) for 28 analyses of brecciated basaltic eucrites. The heavy-line curve is the summed age probability.

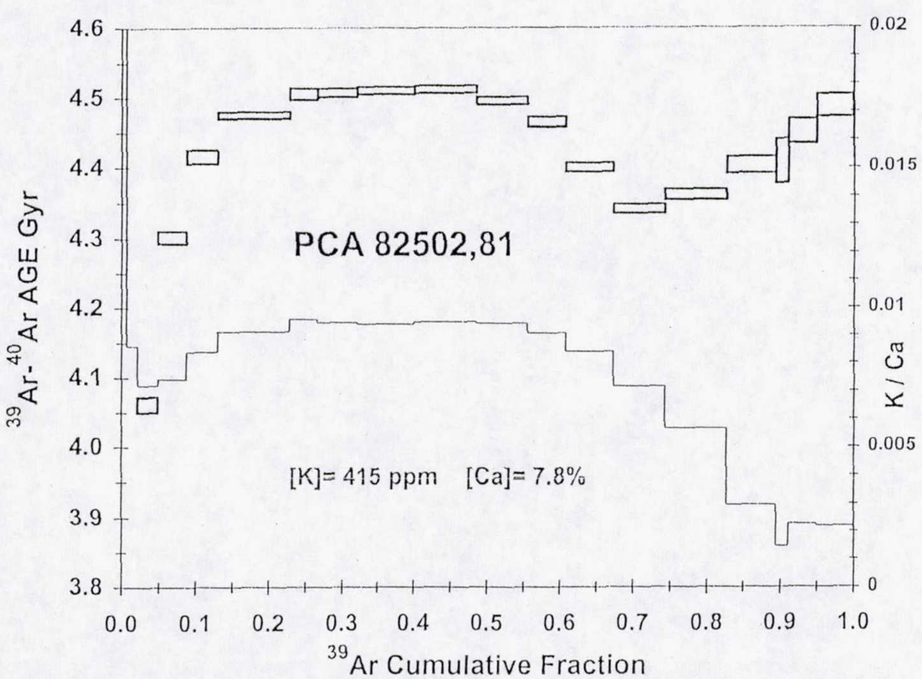

4.6
4.5
4.4
4.3
4.2
4.1
4.0
0.012
0.01
0.008
0.006
0.004
0.002
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
^{39}Ar-^{40}Ar AGE Ga
K / Ca
^{39}Ar Cumulative Fraction
QUE97053,8
[K]= 480 ppm, [Ca]= 8.9%
Give ages on figures?


4.6
4.5
4.4
4.3
4.2
4.1
0.1
0.01
0.001
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
4.453 +-0.015 Gyr
4.473 +-0.012 Gyr
^{39}Ar-^{40}Ar AGE Ga
K / Ca
^{39}Ar Cumulative Fraction
GRA98098 WR
[K]= 575 ppm, [Ca]= 9.54%

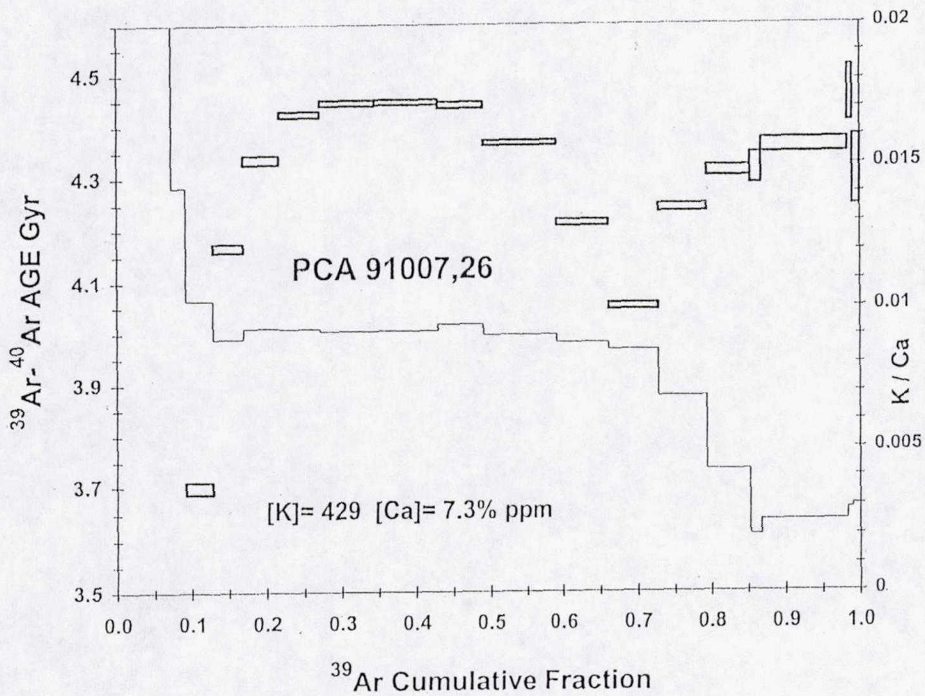
Bogard and Garrison, Fig.1c



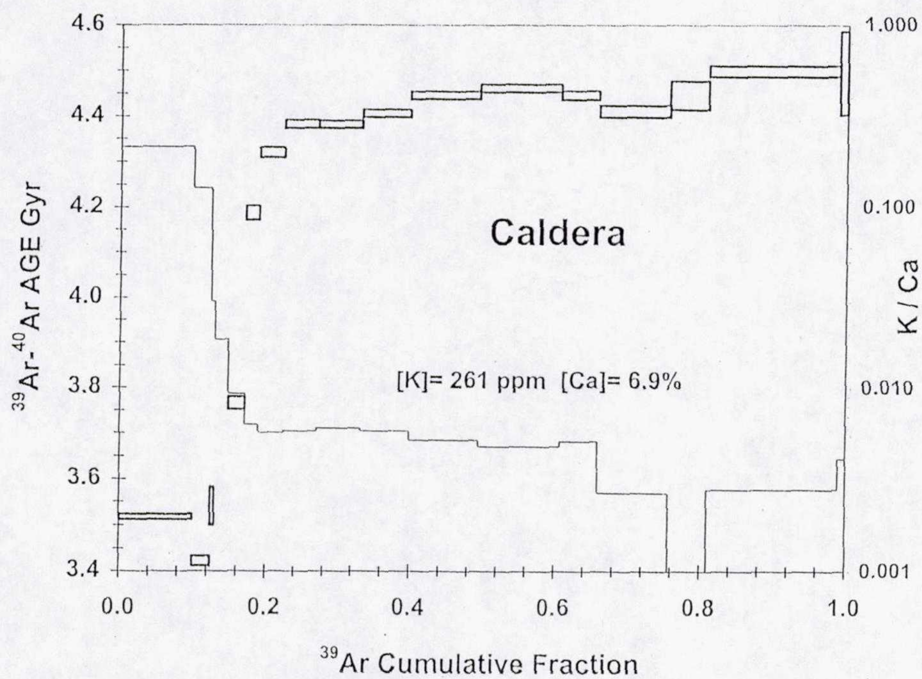
Bogard and Garrison, Fig. 1d



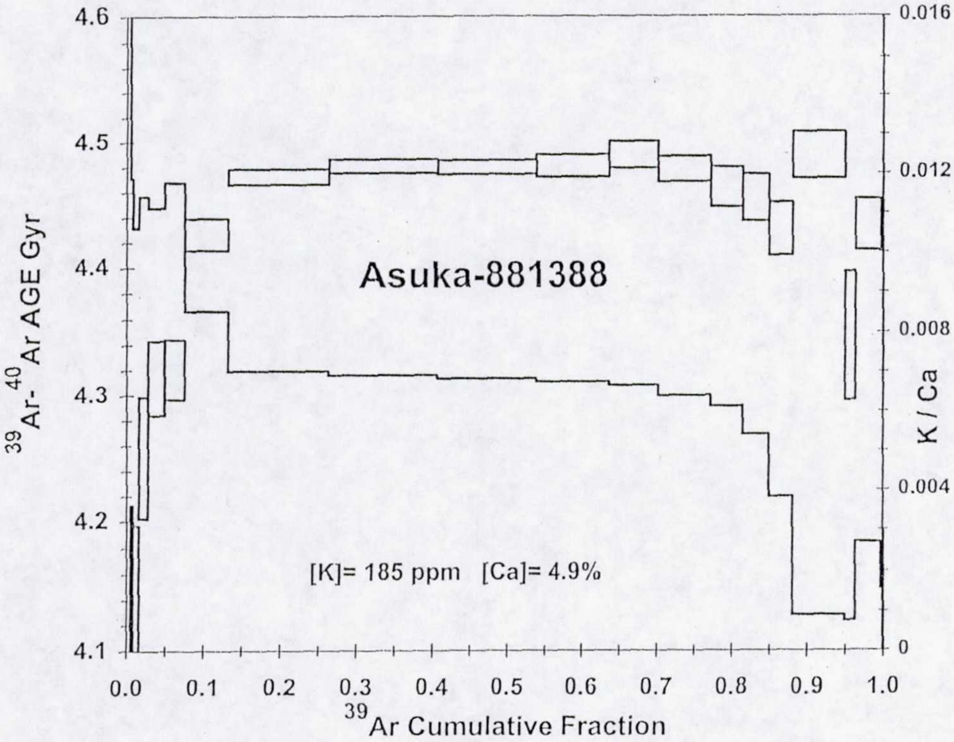
Bogard and Garrison, Fig.1e



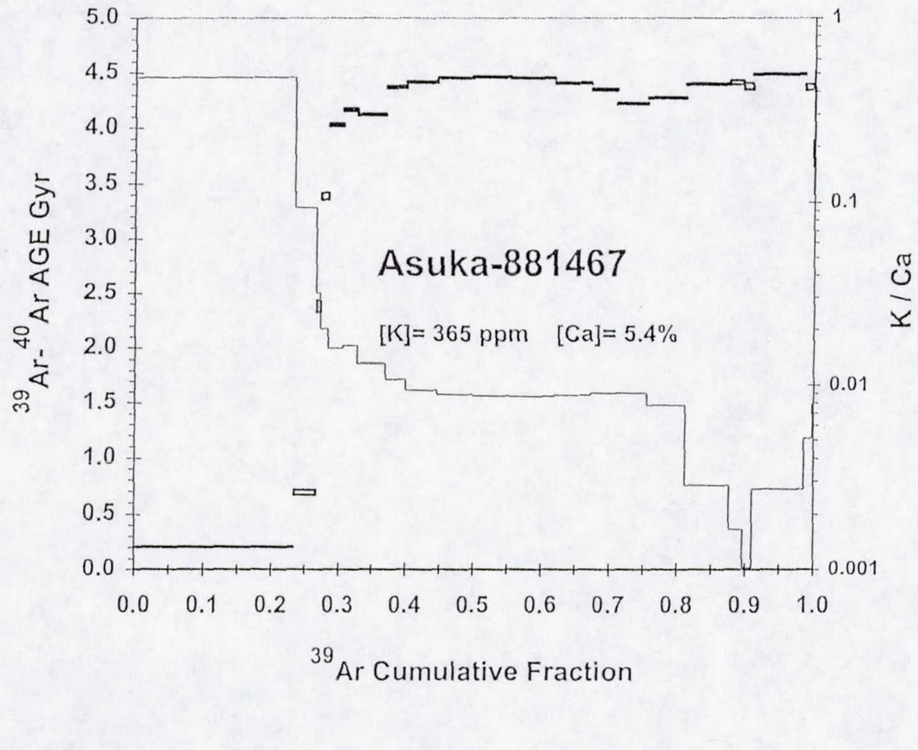
Bogard and Garrison, Fig. 1f



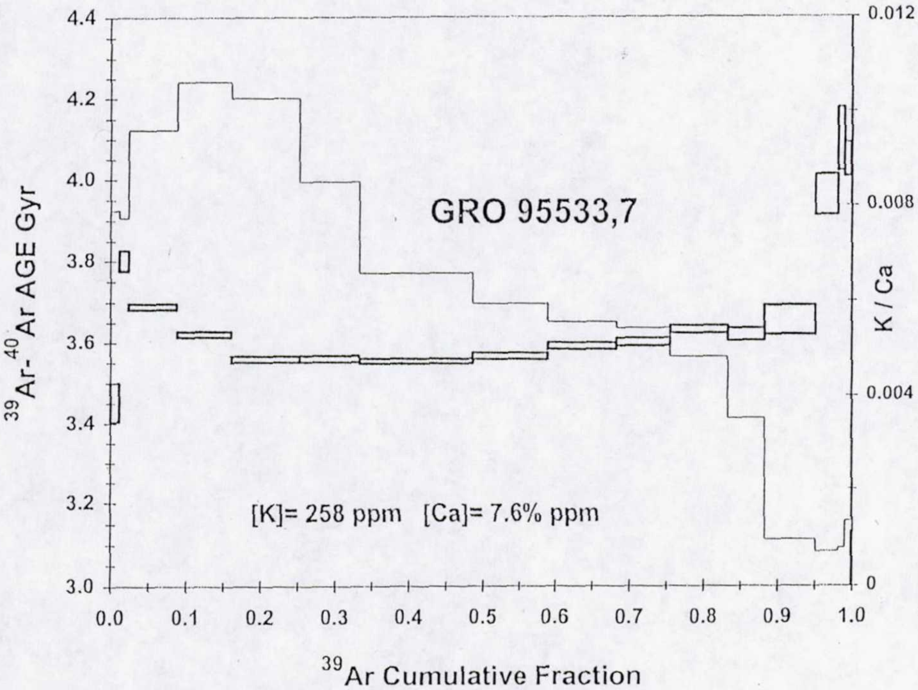
Bogard and Garrison, Fig.1g



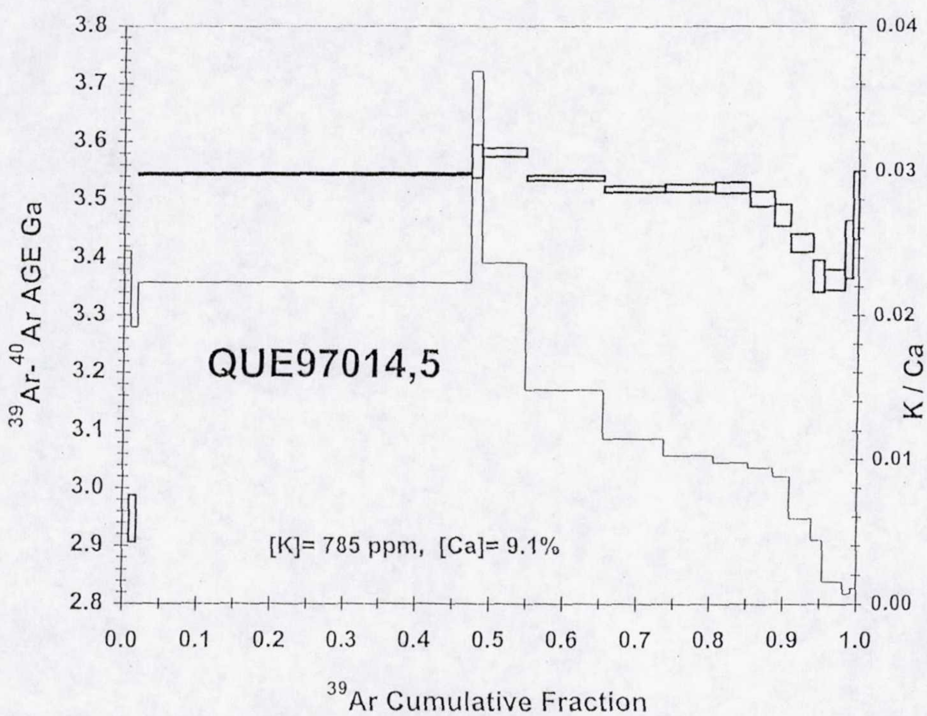
Bogard and Garrison, Fig. 1h



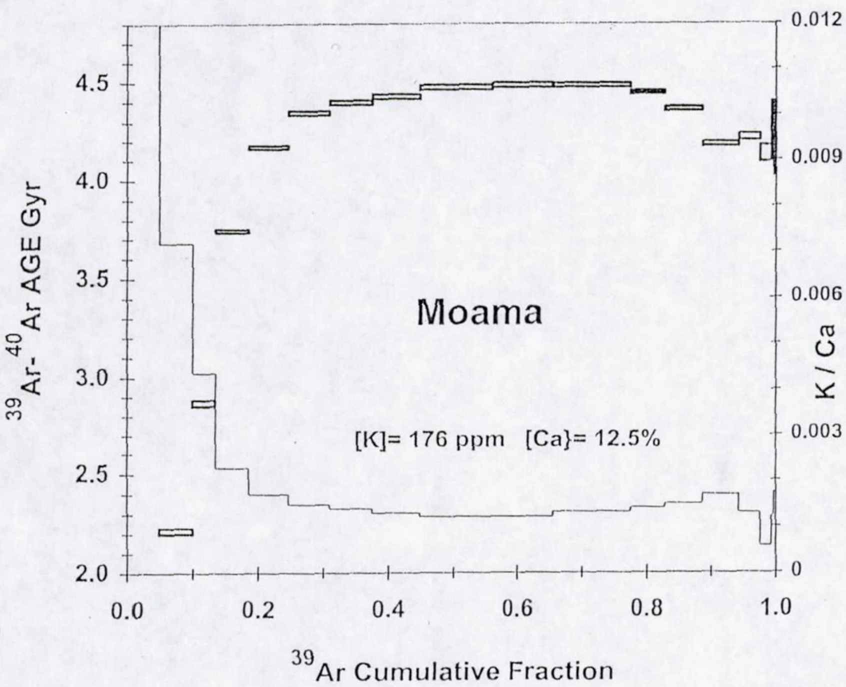
Bogard and Garrison, Fig. 1i



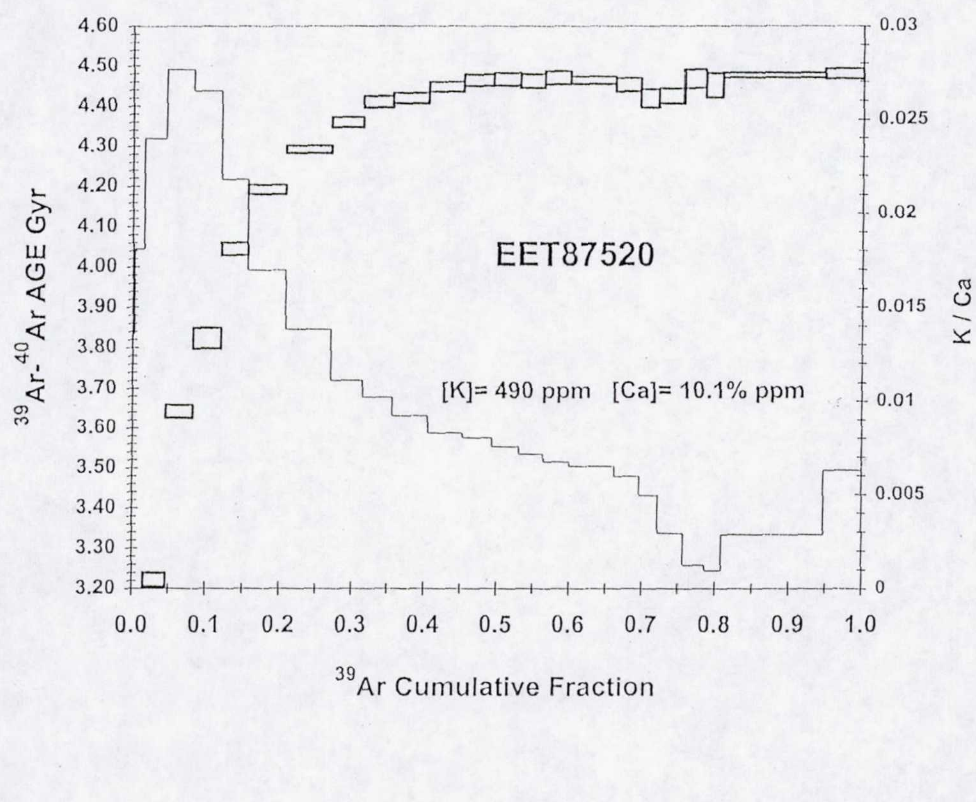
Bogard and Garrison, Fig. 1j



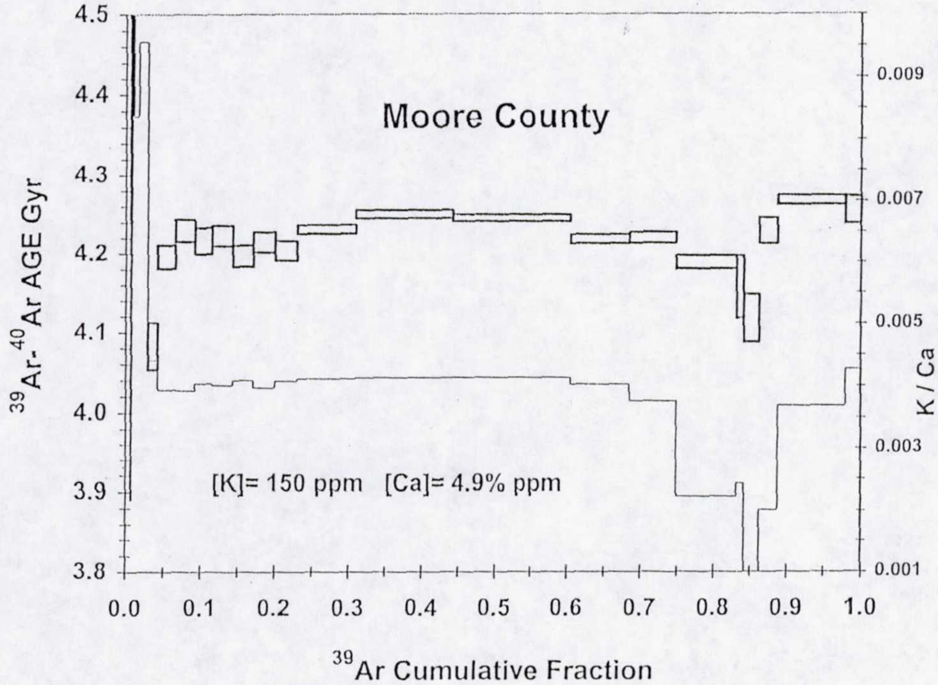
Bogard and Garrison, Fig. 2a



Bogard and Garrison, Fig. 2b



Bogard and Garrison, Fig. 2c



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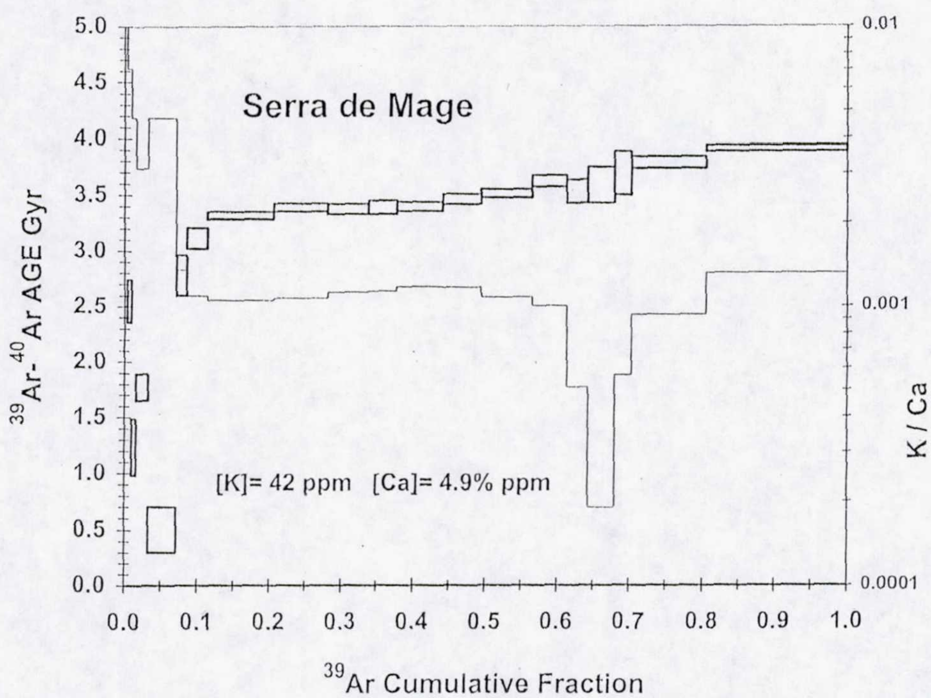

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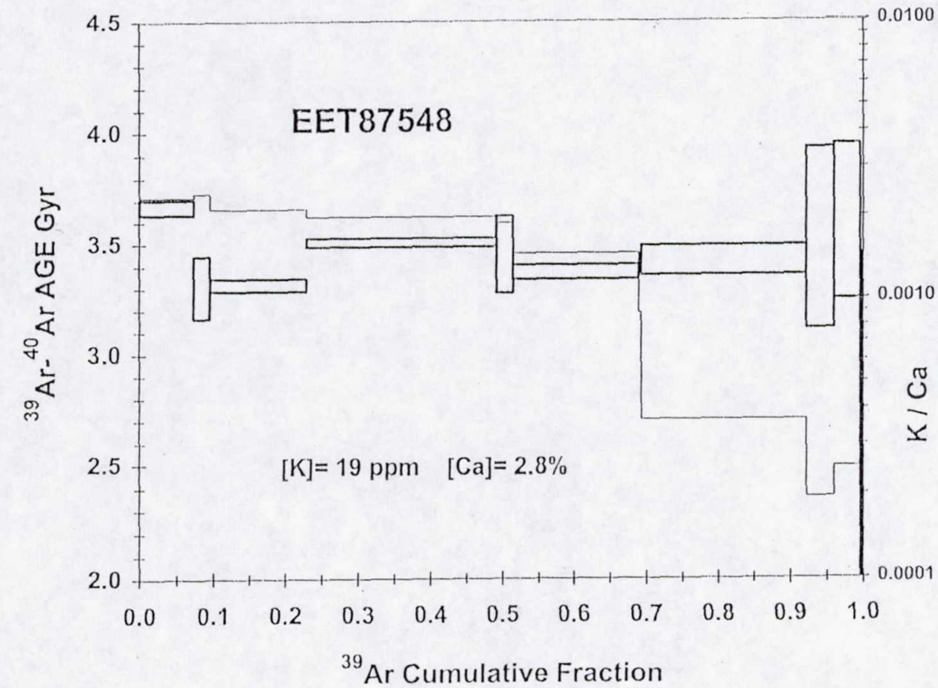

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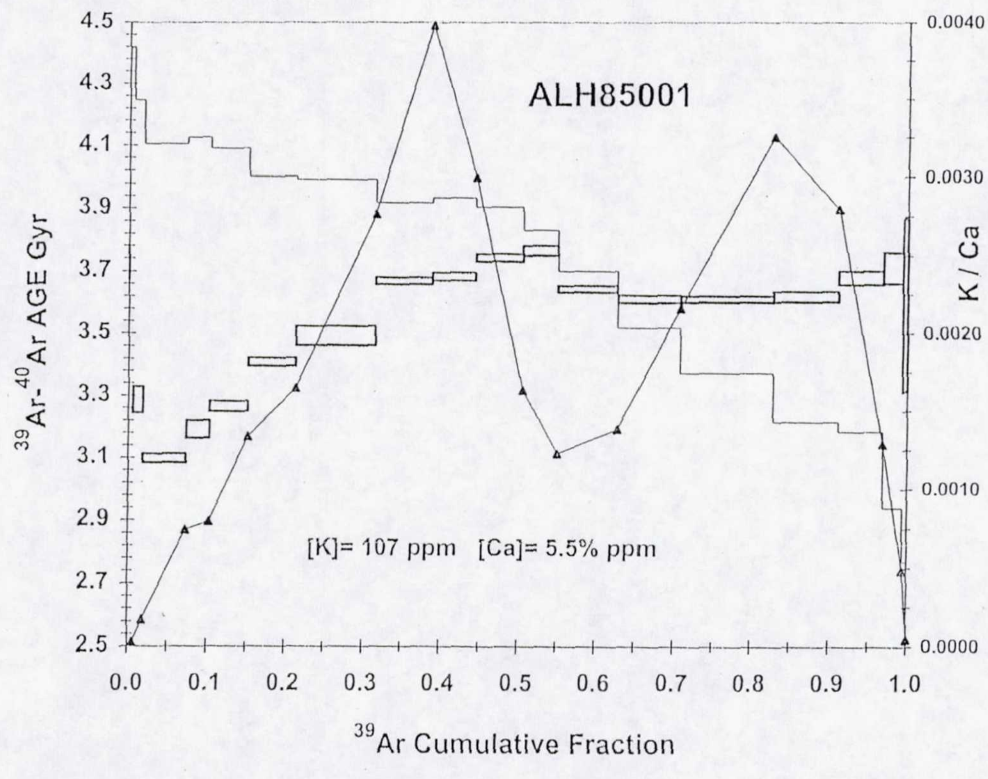
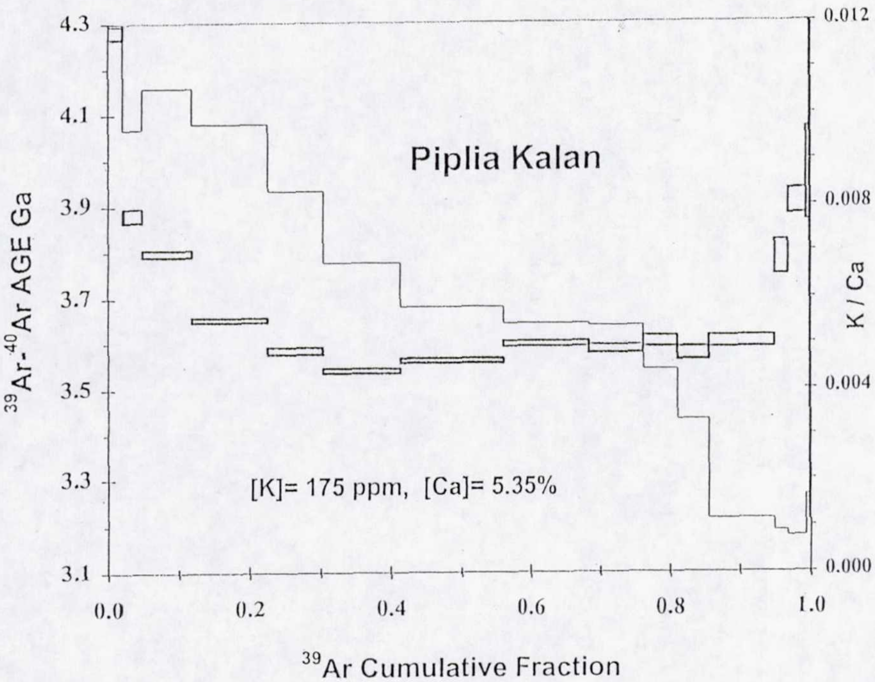
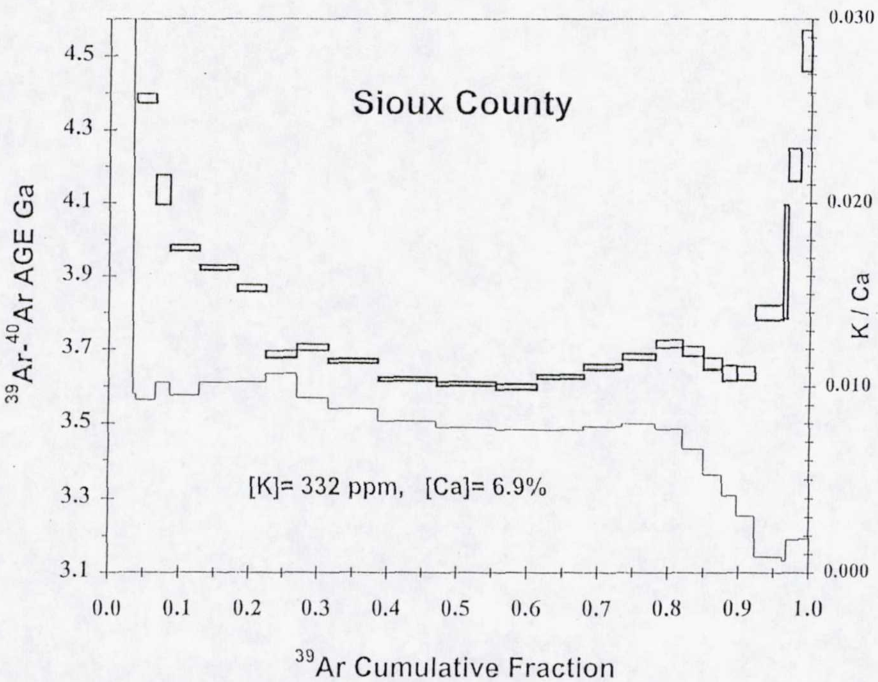


Bogard and Garrison Fig. 3a



Bogard and Garrison, Fig. 3b



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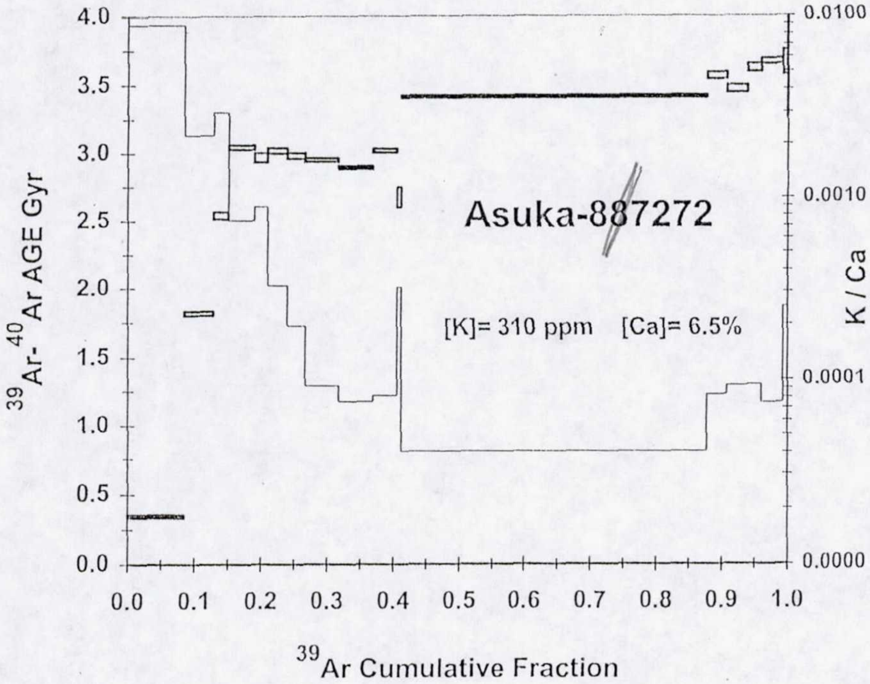

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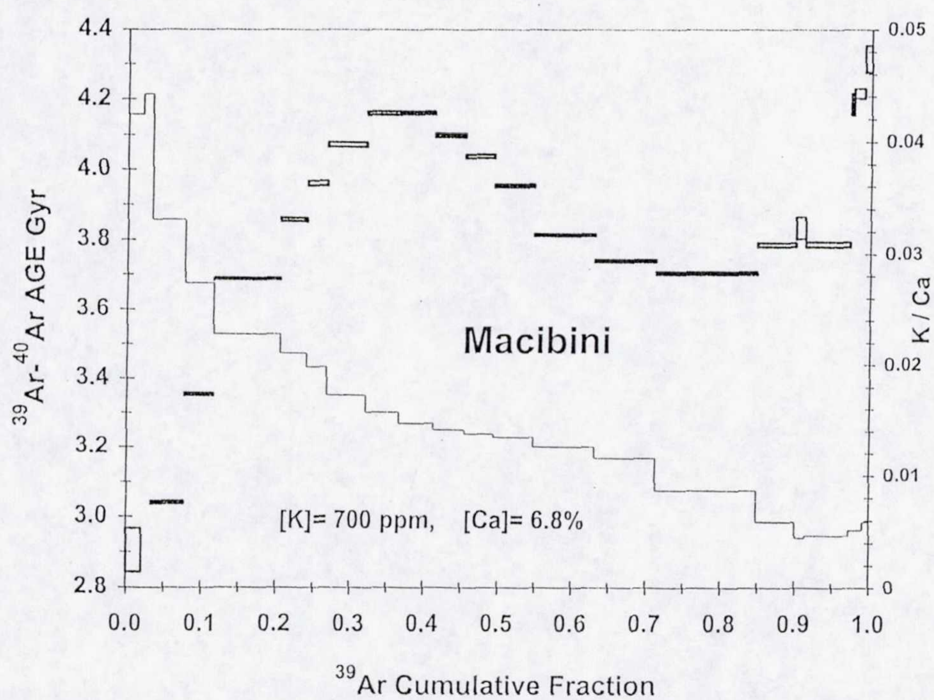

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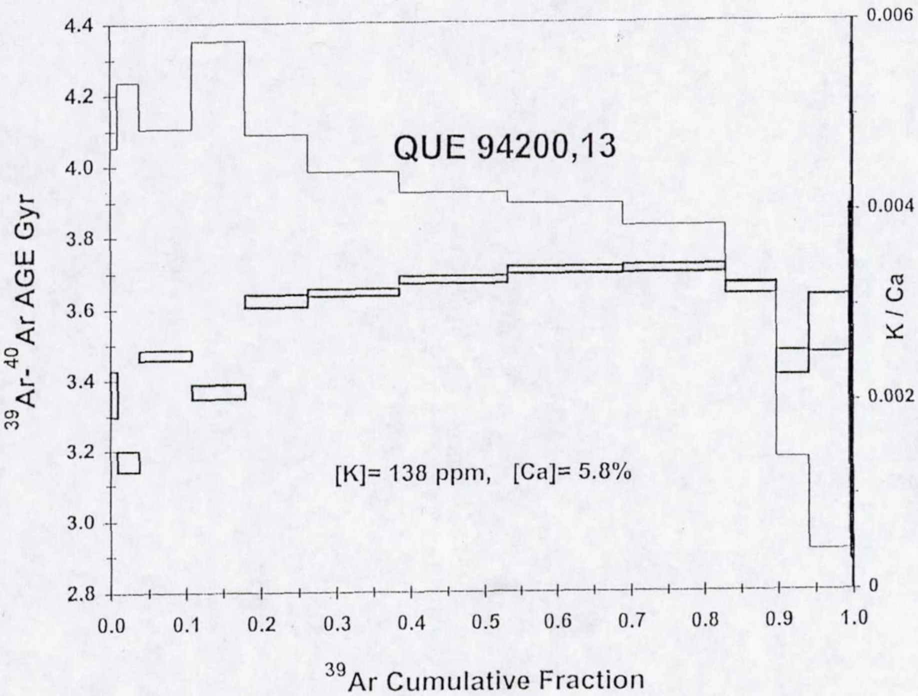

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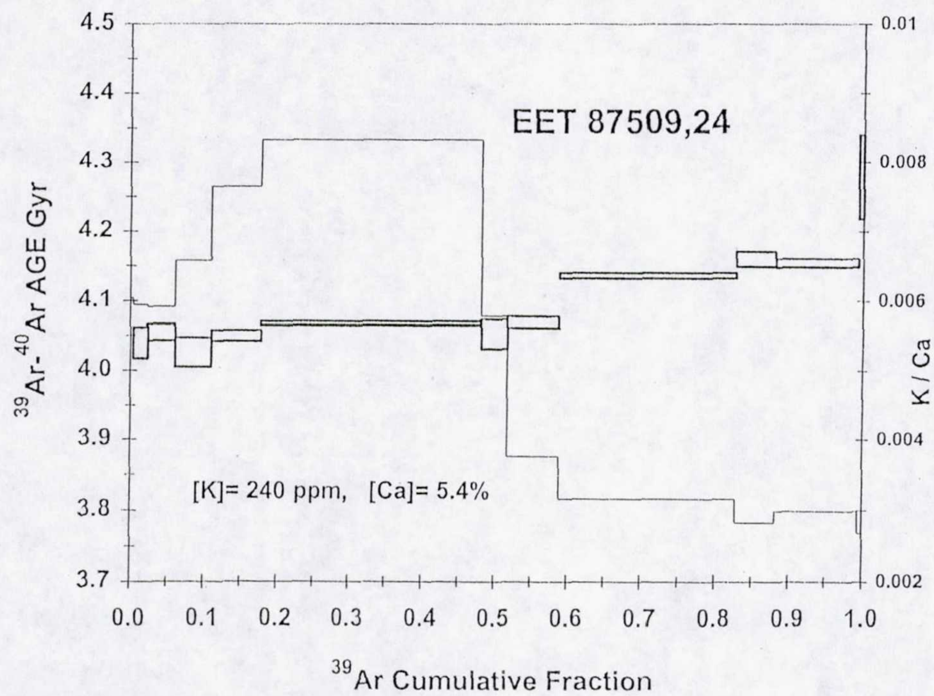

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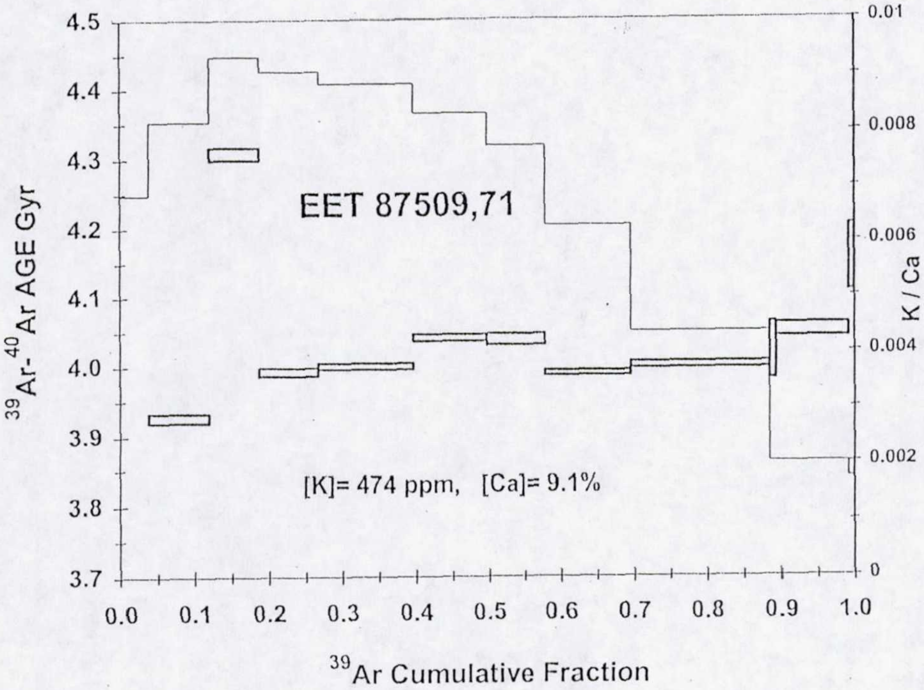

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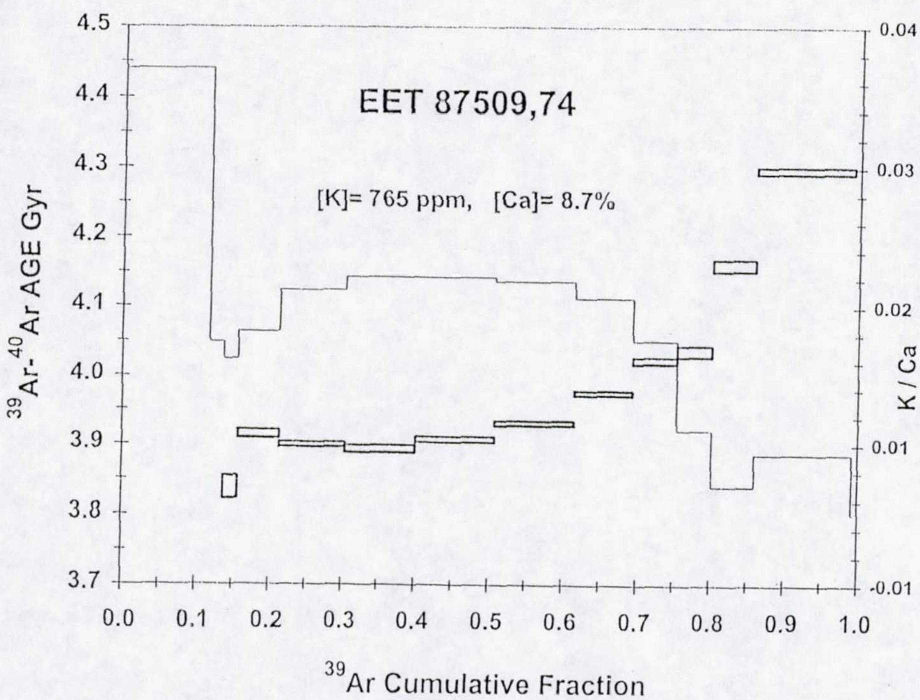

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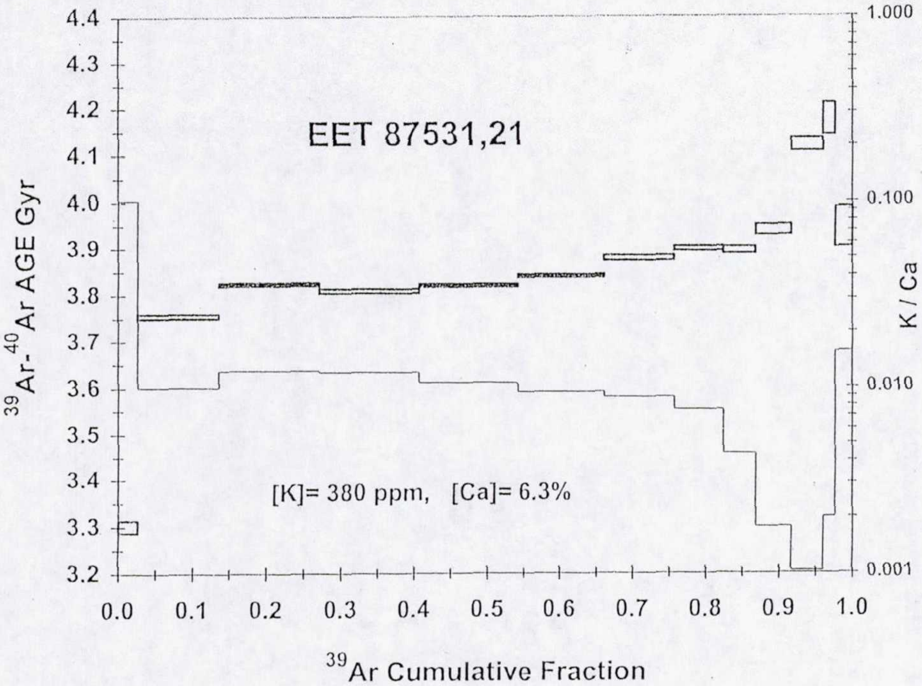

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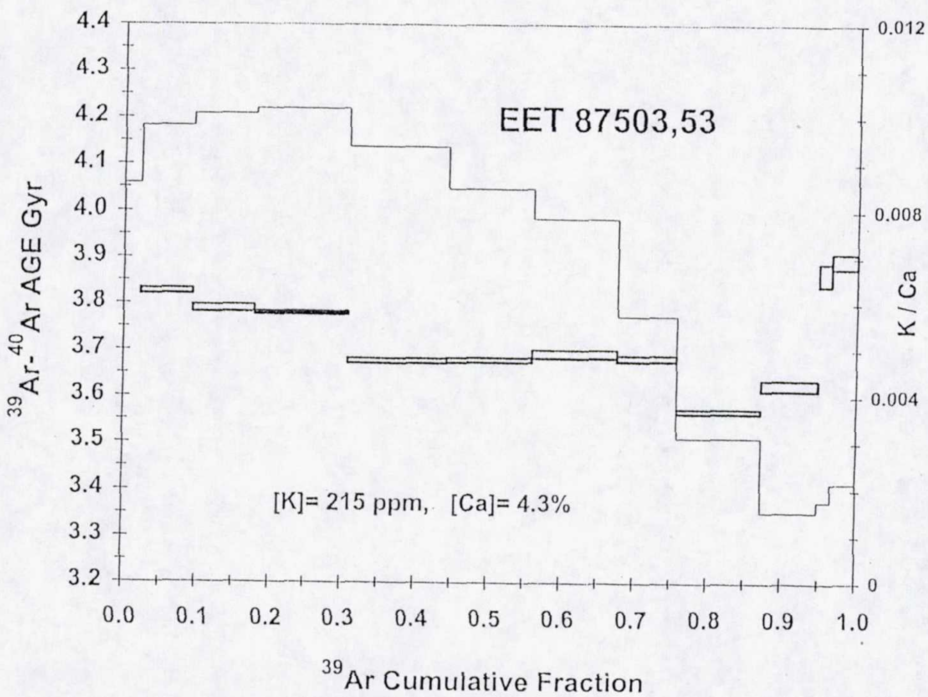

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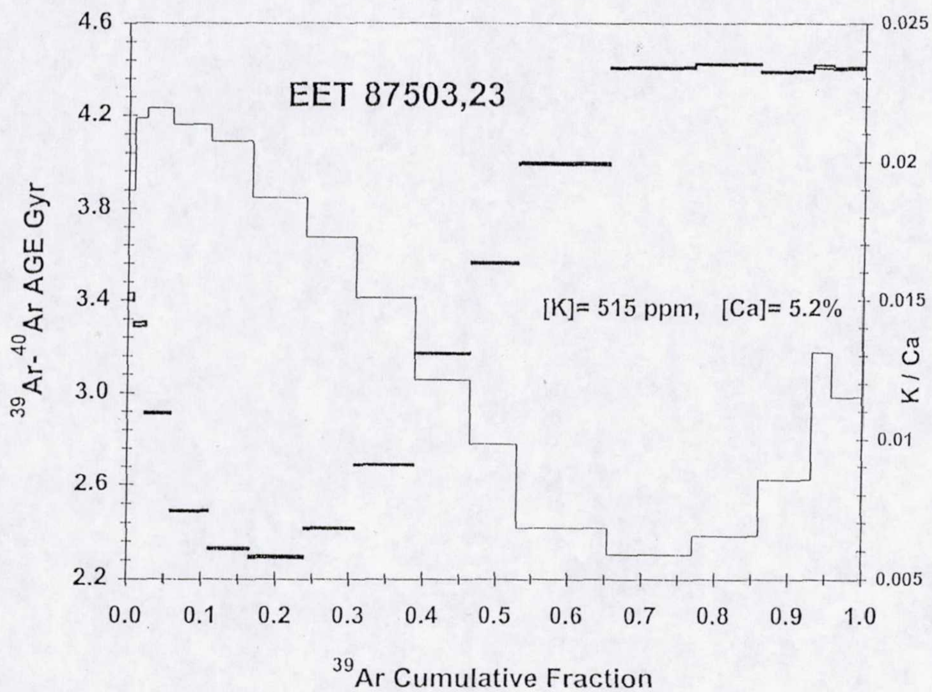

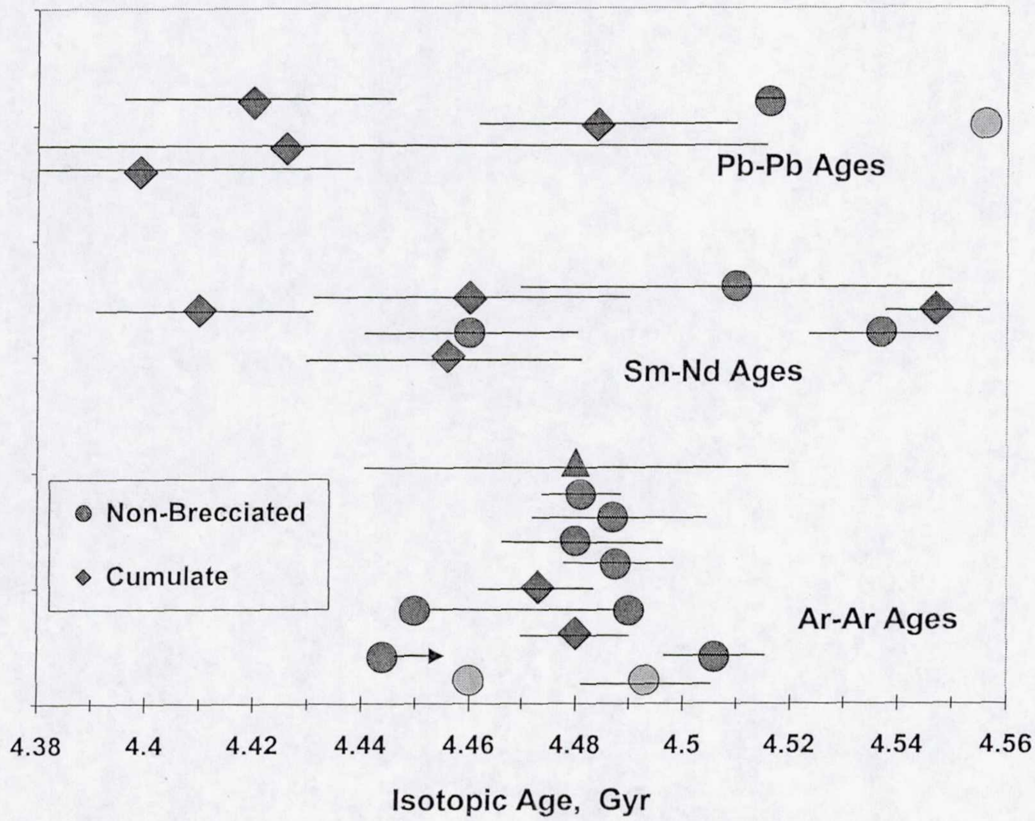

Figure 5. Bogard & Garrison

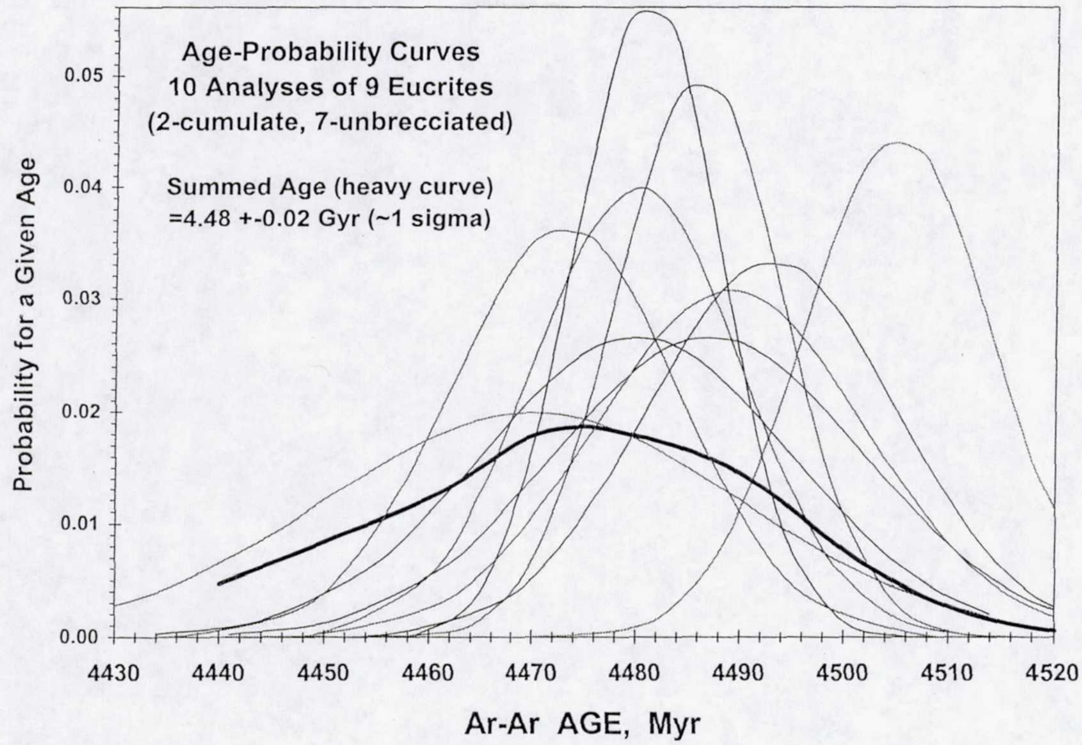

Figure 6. Bogard & Garrison

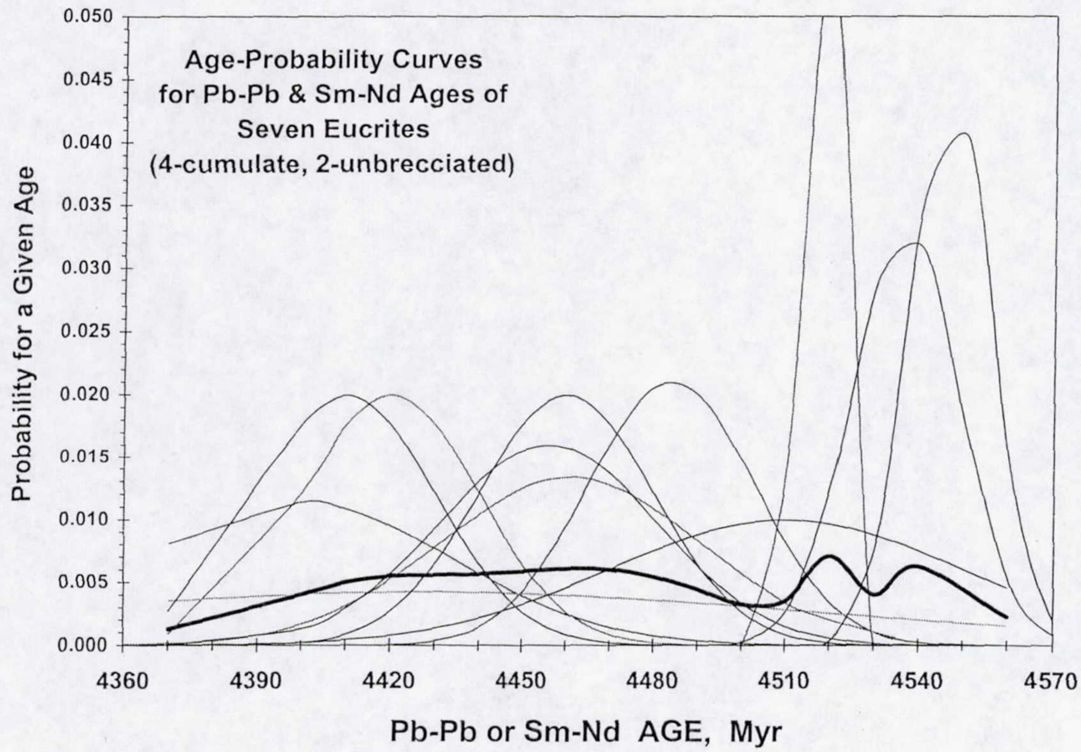

Figure 7. Bogard & Garrison

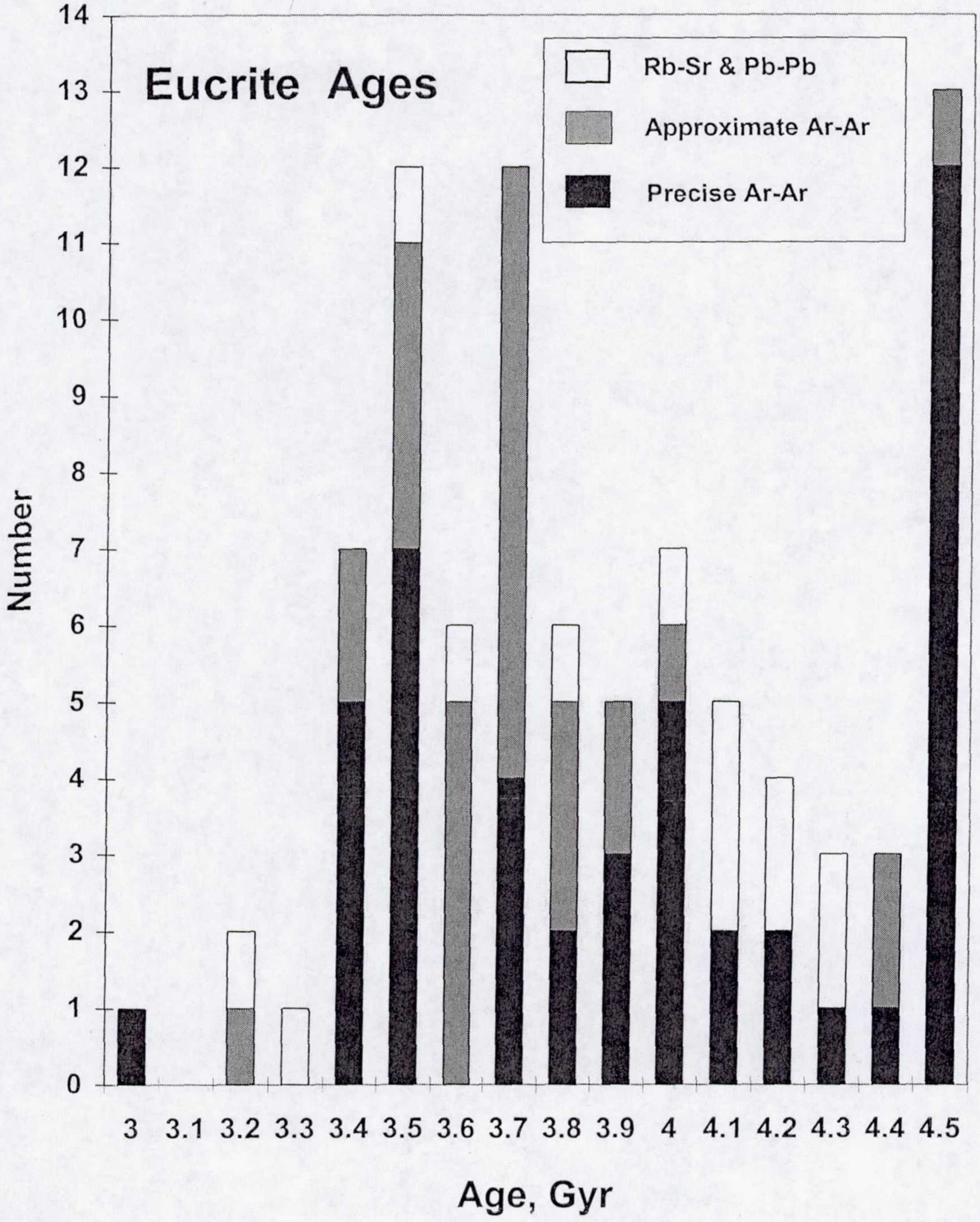

Figure 8. Bogard & Garrison

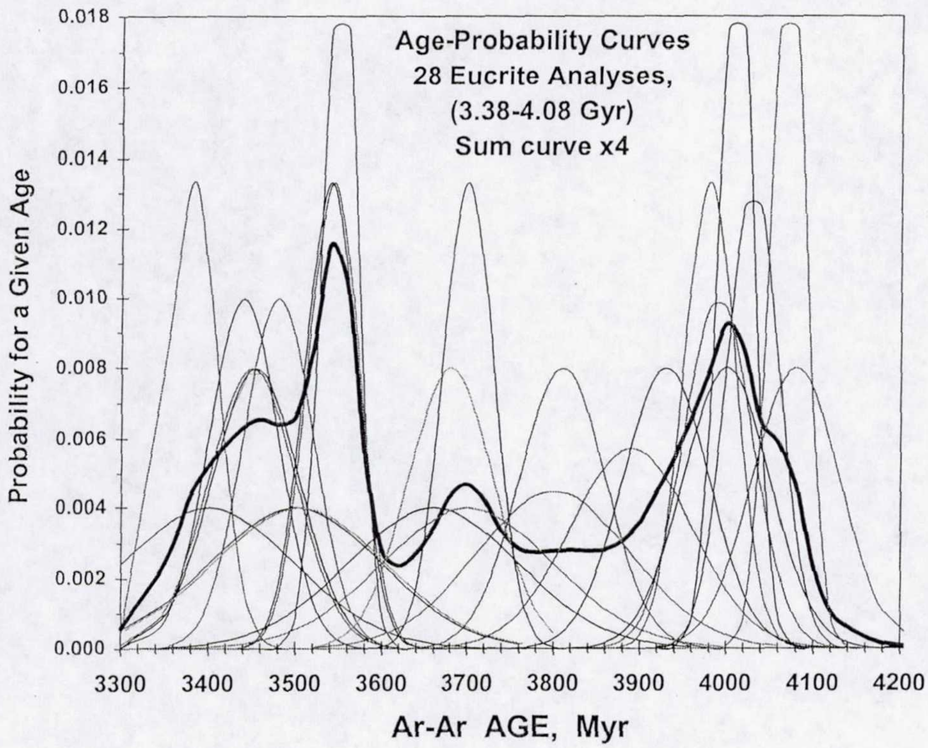

Figure 9. Bogard & Garrison